2001

The assessment of satellite remote sensing as a tool for determining sea surface temperatures in nearshore environments

Fabienne Faskel
Edith Cowan University

"The Assessment of Satellite Remote Sensing as a Tool for Determining Sea Surface Temperatures in Nearshore Environments"

By

Fabienne Faskel

This thesis is submitted in partial fulfillment of
the requirements for the award of
Bachelor of Science (Environmental Management) Honours
at the School of Natural Sciences,
Edith Cowan University, Joondalup.

DATE OF SUBMISSION: 23rd November, 2001

USE OF THESIS

The Use of Thesis statement is not included in this version of the thesis.

Declaration

I certify that this thesis does not, to the best of my knowledge and belief: incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education; contain any material previously published or written by another person except where due reference is made in the text; or contain any defamatory material.

Signature

Date 19 04 02

Author's Note

Satellite remote sensing is a time and revenue-effective means of acquiring a wide array of data, which may be used for environmental management purposes. It is still, however, an under-utilised technology.

This study has aimed to explore the potential of satellite remote sensing for acquiring sea surface temperatures in coastal environments. It is hoped that these findings will prove fundamental to nearshore ecology and biology researchers, and management agencies alike.

> **"Utilisation of spacecraft for solving the problems of [the environment] provides a good example of the peaceful use of space. Taking into account the interests of the present and future generations, these is no other more favourable area of space technology application than environmental protection, to study the natural resources of the Earth and control their rational utilization and reproduction. We hope that in the forecoming years international co-operation in this field will be further expanded"**

L.E. Mikhailov

USSR State Committee on Forestry

(WCED, 1990)

ACKNOWLEDGEMENTS

Without the expertise, time and dedication of the following persons, this thesis and associated research would not have been possible. I thank you all sincerely.

Alan Pearce (CSIRO Marine Research) whose superb expertise and supervision, project design, analysis assistance and patience has made this research not only possible, but also inspiring. And to Valerie Pearce, a great many thanks for referencing and literature assistance.

Dr. Glenn Hyndes, at Edith Cowan University; whose help with supervision, technical aspects, editing, guidance, material supplement and advice was most greatly appreciated.

Mr. Cameron Hill my brilliant research assistant without whom this research would not have been possible, I thank you for your time, effort and endurance.

Mr. Brad Mettam and staff at Edith Cowan University, whose help with transportation, field equipment, funding and safety provisions made this project a great success.

Thanks go also to Claire Wright and the Rangers at Rottnest Island whose help with equipment retrieval and deployment, literature review and data supplement made this research most enjoyable and rewarding.

Dr. Barry Hutchins (Museum of Western Australia), I thank you all for your help with various aspects involved with the research, photographic supplements, data collation and your most valuable field notes on coral bleaching at Parker Point;

And thank-you to my family and friends for all your support and encouragement throughout the year. I couldn't have done it without all your strength and support.

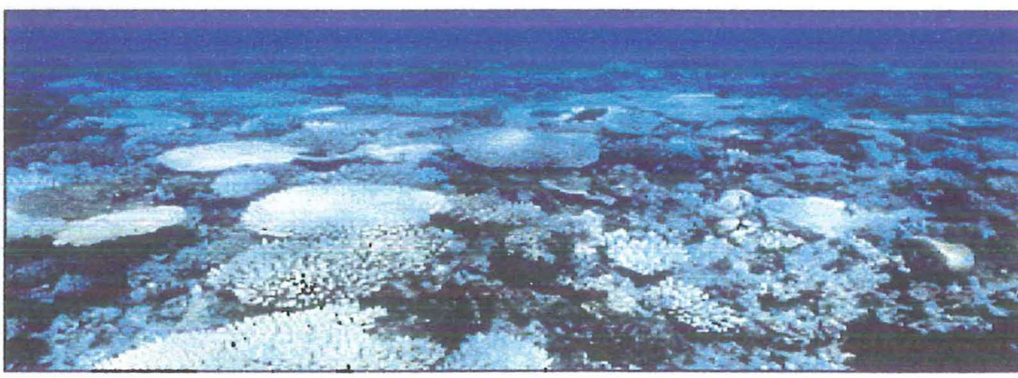

Table of Contents **Page**

List of Figures **Page**

List of Tables **Page**

APPENDICIES

ABSTRACT

The use of satellite remote sensing for environmental management applications has seen a marked increase over the past decade. Remotely sensed data are obtainable for a variety of parameters, such as mineral exploration, species migration, and for determining sea surface temperatures (SSTs). This study examined whether satellite remote sensing is a viable option for determining SSTs in coastal waters, as traditionally this application has only been applied to open-ocean, offshore waters.

SSTs in the nearshore waters of Rottnest Island, Western Australia, were determined using *in situ* temperature loggers and remotely sensed satellite data. Initially the accuracy of the satellite sea surface temperature extraction algorithms was examined, and subsequently spatial and temporal temperature variability around the island was examined. These findings were applied to investigate the relationship between sea surface temperatures and incidences of coral reef mortality between 1995-2001.

The results showed that satellite remote sensing is a viable option for determining SSTs at least 1km offshore. It was found that these offshore data were also representative of more nearshore temperatures. Such findings may be considered of significant consequence when examining marine systems in a management perspective, where issues raised include those associated with coral reef systems, which often subsist in nearshore areas, and may be thermally influenced. This study found that coral bleaching phenomena showed little relation to periods of increased SST, suggesting that other factors besides SST, may be influencing coral mortality at Rottnest Island. The future use of satellite remote sensing to extract SST data in nearshore regions will aid in marine ecosystem management by determining possible relationships between temperature and environmental events such as coral mortality.

CHAPTER 1.0
INTRODUCTION

1.1 Satellite Technology and Remote Sensing

Satellite remote sensing is being increasingly used for environmental monitoring, including of the oceans. Remote sensing has been defined as 'the science of making measurements of an object without actually coming into contact with it' (Myers, 1987). A remote sensing system consists of three main elements: a platform (the satellite); a set of sensors mounted on the platform to take measurements (radiation detectors); and an analysis system to interpret the data received (often a Geographic Information System - GIS) (Myers, 1987). The Advanced Very High Resolution Radiometer (AVHRR) is the term given to the sensors of the remote sensing system, which measure the infrared, and visible regions of the electromagnetic spectrum. This allows for a wide array of applications and natural resource management, such as charting geological terrain, determining mineral deposits, and measuring sea surface temperatures (SSTs) (Myers, 1987; Pattiaratchi, 1992). The ability to measure SSTs using remote sensing in oceanic waters, has lead to many oceanographical advancements including the detection of the Leeuwin Current, which flows southwards along the Western Australian coast (Pearce & Pattiaratchi, 1997). In the coastal and oceanic environment, remote sensing has the ability to determine, not only Current movement, but also a multitude of factors, including chlorophyll a' concentrations, turbidity, sediment transport, bathymetry, and sea surface temperature (Bernstein, 1982; Pearce & Pattiaratchi, 1997). The knowledge of these parameters allows environmental managers to monitor the dynamics of the marine environment, and to manage it appropriately.

To date satellite remote sensing is the only feasible means of monitoring, on a regular basis, the large global expanse of oceanic surface waters (Pearce & Pattiaratchi, 1997). Numerous satellites orbit the earth, however, the National Oceanographic and Atmospheric Administration's (NOAA) AVHRR series of satellites have been most commonly used for measuring SSTs (Juppenlatz & Tian, 1996; Myers, 1987; Pearce & Pattiaratchi, 1997).

Satellite remote sensing systems obtain SST measurements by utilising 'bands' of differing wavelengths in order to measure the radiation from the 'skin' or top millimeter of the ocean's surface. As explained by Pearce *et. Al.* (1997), the temperature in the surface (skin) of the ocean is influenced by radiative processes and both incoming and outgoing surface heat fluxes. Vertical mixing ensures that the skin temperature is generally close to the temperature of the upper few metres of the water column, ('bulk' temperature). Under most conditions, the skin SST measurement is representative of the bulk temperature (Gohin & Langlois, 1993; Myers, 1987), with the exception of extreme circumstances of wind-still or very poorly mixed/flushed marine environments. In theory, NOAA sensors are capable of resolving ocean skin temperature measurements to within 0.12°C. However, in practice, atmospheric and other effects make the resolution closer to 0.6°C over the sea (Llewellyn-Jones *et. al.* 1984; Myers, 1987; Chiswell *et. al.*, 1992).

The need for satellite readings as opposed to manual (*in situ*) measurements of SST is apparent when examining large expanses of water, such as the Western Australian coastline, which stretches for over 12 000km (Jarvis, 1986). The need for remote sensing is further highlighted when examining hazardous or rough coastal conditions. Satellite remote sensing of SSTs also provides historical data set construction, by accessing databases that span back several decades. In particular, the use of satellite remote sensing in coastal environments will be inherently important to fisheries management

(Strong, *et al.*, 1996). Many species of fish and other marine organisms are sensitive to changes in water temperature. For example, tuna tend to congregate about warm fronts in ocean currents, and the growth of abalone and some other crustaceans depend on water temperature and circulation patterns (Myers, 1987). SST determination in coastal waters can therefore be used to aid in determining likely locations for certain types of fisheries, to monitor fish and larval recruitment, spatial distribution (Hutchins & Pearce, 1994), and to facilitate effective management of many marine organisms (Gosliner *et. al.*, 1996; Myers, 1987; Wellington *et. al.* 2001).

1.2 Satellite Technology in Nearshore Environments - A Tool for Ecosystem Management -

Sea surface temperatures are measured by the NOAA satellite in 1.1 x 1.1 km 'pixels'. The relatively large size of these pixels has restricted SST retrieval to the open ocean environments, due to factors associated with 'land contamination', which occurs when the SST measurement of a pixel contain data derived from both land and water. Previous studies assessing the accuracy of remotely-sensed satellite data have thus only been carried out in open-ocean environments (e.g. Fox *et al.*, 2000; Stramma *et. al.*, 1986; Yokoyama & Tanba, 1991). These studies have been undertaken exclusively in open ocean environments to compare satellite data with fixed buoy and *in situ* data and concluded that satellite and *in situ* data were in excellent agreement for cloud-free days (Fox *et. al.*, 2000; Stramma *et. al.*, 1986; Yokoyama & Tanba, 1991. Previous studies have not, however, utilised remotely-sensed data derived from nearshore or coastal regions, due to problems associated with land contamination (see Section 2.4). Acquiring coastal SSTs will allow for nearshore fisheries management, coastal climatology construction nearshore reef monitoring and management, and other coastal applications that require temperature data.

1.3 Coral Bleaching Phenomena

As previously stated, satellite remote sensing applications may be used for the management of natural resources, both aquatic and terrestrial. Satellite technology is constantly being advanced, and it is postulated that the use of remote sensing in nearshore environments will ultimately allow for the augmented management of coral reef systems, which are commonly found in such nearshore/coastal environments. Previously, due to technological restrictions, satellite remote sensing has only been applied in open-ocean environments, and thus little satellite data are available for nearshore regions. Coral bleaching has become one of the largest global threats facing our tropical marine ecosystems (IUCN, 2000). Under stress, corals expel symbiotic zooxanthellae, which provide them with a major food source and their colour, thus, these micro-algae are vital to the survival of the corals and, of course, the reefs they produce (NESDIS, 2001). The "bleaching" event turns the corals transparent, pale, or unusual colours, and the coral polyps enter a starving stage, leaving the coral unable to grow or reproduce (IUCN, 2000). With increasing and/or continual stress the coral will die, but if the stress subsides, the coral will typically recover. Depending on the species and the magnitude and duration of the stress, recovery and restoration time is variable (IUCN, 2000).

Since 1982, coral reefs world-wide have been subjected to an increased frequency of coral bleaching (Wellington, *et. al.*, 2001). An extreme global bleaching event occurring in the late 1990s, giving rise to fears of further high- mortality events, especially with the rise in global air temperatures and the resultant enhanced greenhouse effect (IUCN, 2000). Although scientists have been observing coral bleaching for over 20 years, it was only during this mass global coral bleaching event that they began to hypothesise that sea surface temperature might influence this process (NESDIS, 2001). Previously, mechanical processes, such as wave action, or physico-chemical factors, such as salinity, had been linked with coral mortality (SCUBA II, 1998). Global Coral Reef Alliance scientists began researching coral bleaching events, and found that every known mass bleaching event followed periods when mean maximum sea surface temperatures were elevated on average for one week by ≥ 1 °C. This week of elevated temperatures that devastate corals is commonly known as a degree-heating week (DHW), and compared with other marine organisms, shows that coral reefs are the most temperature sensitive of all ecosystems (Wellington *et al.*, 2001), where a prolonged rise in temperature of only 1 °C, can devastate an entire coral community, often with little chance of replenishment.

Coral bleaching has only been investigated globally during the past decade, and although widely discussed in scientific circles, the paucity of information relating to climatic and environmental effects, has resulted in a lack of understanding and appropriate management. The amount of coral bleaching that occurs is likely to be considerably underestimated since most observers only recognise the severe cases when most of an entire coral community have turned completely white in appearance. Many more cases of milder bleaching, which cause only the most sensitive coral species to turn pale, are not usually recognised (NESDIS, 2001).

It is hoped that the use of satellite remote sensing in nearshore environments will allow for better monitoring and determination of the factors involved with nearshore tropical coral bleaching.

1.4 Study Region - ROTTNEST ISLAND, Western Australia

Rottnest Island (32°S, 115°E) forms part of a chain of limestone islands and reefs that includes Garden Island, Carnac Island, Penguin Island, and Five Fathom Bank, on the continental shelf approximately 20km west of Fremantle, Western Australia (Playford, 1988). Rottnest Island is 10.5km in length, 4.5km in width, with an area of around 1900 ha (Easton, 1995) (Figure 2.1).

Rottnest Island lies just inside the 50m isobath of the continental shelf. Approximately 30km west of Rottnest Island, the sea floor drops to 4000m (Imberger, 2000). Limestone reefs surround the eastern side of the island, which results in a shallower water depth of approximately 10m on average (Hassell & Kneebone, 1960) (Figure 2.1). Since reefs act as barriers to water flow in the north-south direction, water flows preferentially around the deeper western side of the island. This flow of water around the island is strongly influenced by the seasonal Leeuwin Current and Capes Current (Figure 1.1a and b) (A. Pearce, pers. comm.; Hutchins, pers. comm.).

The coastline of the island is characterised by alternating bays and rocky headlands, the bays generally having wide sandy beaches backed by sand dunes (Hassell & Kneebone, 1960; Playford, 1983). The coastal processes, such as mixing and flushing, experienced in these bays vary significantly (Hodgkin & Di Lollo, 1958; Hopkin, 2001), with Parker Point and Thomson's Bay in particular experiencing high instances of flushing and mixing. Distribution of marine species also varies significantly around the island, with Western Australia's most southerly growing colony of tropical corals found at Parker Point, on the south-eastern tip of Rottnest Island (Figure 2.1) (Hutchins, 1998; Ward, 1994). Extremely few historical data, recording SSTs around Rottnest Island, have been documented, and thus it is optimal to attain satellite data for historical SST extraction and analysis.

1.4.1 The Leeuwin and Capes Currents

The Leeuwin Current is a warm, clear-water, ocean current that flows strongly southwards along the Western Australian coast (Figure 1.1a). Its strength varies throughout the year, with the strongest flow experienced during the winter months (Pearce *et. al.*, 1985; Pearce *et. al.*, 1999; Pearce *et. al.*, 2001). Because of the Leeuwin Current, the continental shelf waters of Western Australia, and Rottnest Island in particular, are warmer in winter, and are also responsible for the presence of true corals at Rottnest Island (Pearce *et. al.*, 2001).

In contrast to the Leeuwin Current, the Capes Current, which flows north, along the southwestern Australian coastline (Figure 1.1b) is at its strongest during the summer months. Transporting much cooler, Southern Ocean waters, the Capes Current commences in the southwest near Cape Leeuwin and flows northwards past Cape Naturaliste and on beyond Rottnest Island. This current transports the cooler Southern Ocean waters (Pearce, *et. al.*, 2001).

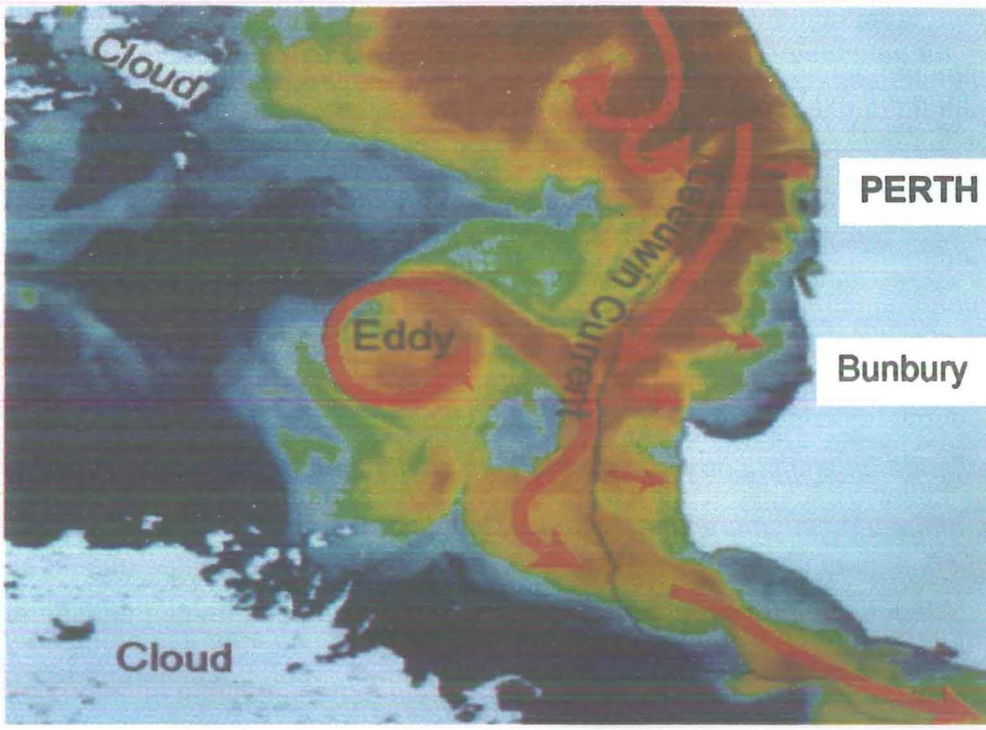

Figure 1.1a Relative positions and directions of the Leeuwin Current in proximity of Rottnest Island, during winter. (Courtesy Pearce, *et. al.*, 2001).

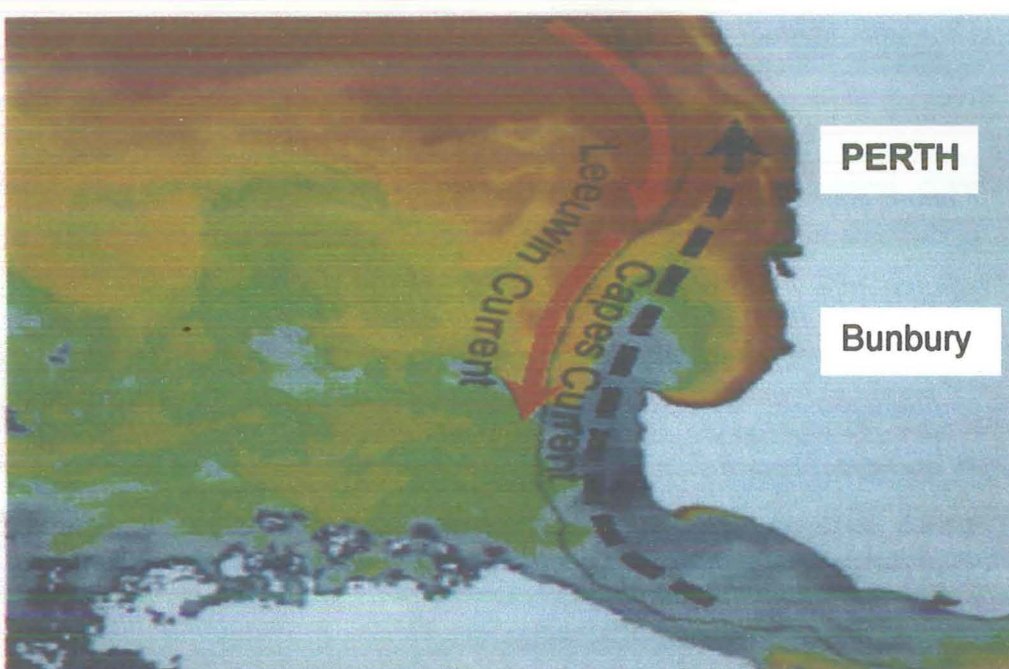

Figure 1.1b Relative positions and directions of the Leeuwin & Capes Currents in proximity of Rottnest Island, during summer. (Courtesy Pearce, *et. al.*, 2001).

1.4.2 Tropical Corals at Rottnest Island

The use of satellite remote sensing in coastal regions would result in the ability to examine historical SST data, thus aiding in marine ecosystem management of tropical corals, for example. It is presupposed that the presence of tropical corals at Rottnest Island is due to transportation of larvae from more northern tropical regions by the Leeuwin Current (Hutchins, 1994). The Leeuwin Current is also thought to be the primary benefactor in the survival of the corals, by providing clear and warm waters to the island. Coral reefs need these warm, clear, and relatively sheltered waters for optimal growth (Gosliner *et. al*, 1996). The distribution of coral reefs at any given point in time is determined by various limiting factors, the most significant of which are water temperature, depth, light intensity, salinity, water turbulence and sedimentation (Gosliner *et. al.*, 1996). The Island's coral fauna, comprising 25 species, is a distinctive component of the marine environment in the lower west coast of Western Australia (Veron and Marsh 1988).

Most of Rottnest Island's nearshore limestone reefs are algal covered (Hutchins, 1999). These algae smother corals by preventing coral zooxanthellae colonisation and photosynthesis (SCUBA II, 1998). It is found that algae commonly grow on previously killed corals and are thus not considered the cause of death, but rather the cause for non-recovery of the already bleached corals (IUCN, 2000). Certain areas around the island show rich tropical coral abundance, of which *Pocillopera damicornis* is the dominant species (Figure 1.2a) (Hutchins, 1998). This coral belongs in the group of hermatypic or 'reef-building' hard corals (Gosliner, *et. al.*, 1996), which provide most of the framework of a living coral reef. Thus any mortality to hermatypic corals affects the entire reef ecosystem. Hermatypic corals generally prefer shallow, warm, protected, clear oceanic water (Gosliner, et. al, 1996; Hutchins, 1999; IUCN, 2000), and due to the presence of these conditions, are found in higher abundances at Parker Point, on the southeastern tip of Rottnest Island, than anywhere else around the island. The optimum temperature for the growth of hermatypic corals and the development of coral reefs is 18-28°C (Garrabou *et al.*, 2001; Gosliner *et al.*, 1996; Hutchins, 1999; IUCN, 2000). At temperatures below 18°C coral growth is usually limited or ceases entirely, while temperatures above 28°C frequently induce coral bleaching (Figure 1.2b) especially if these temperatures contribute to a degree-heating week (Gosliner *et. al.*, 1996).

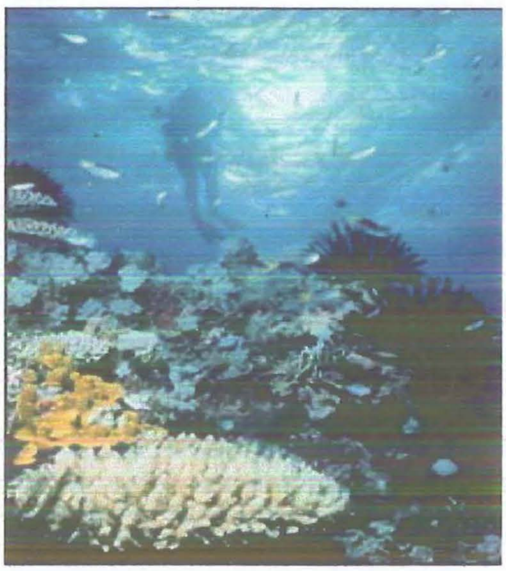

Figure 1.2a - A healthy coral community such as those present at Parker Point.

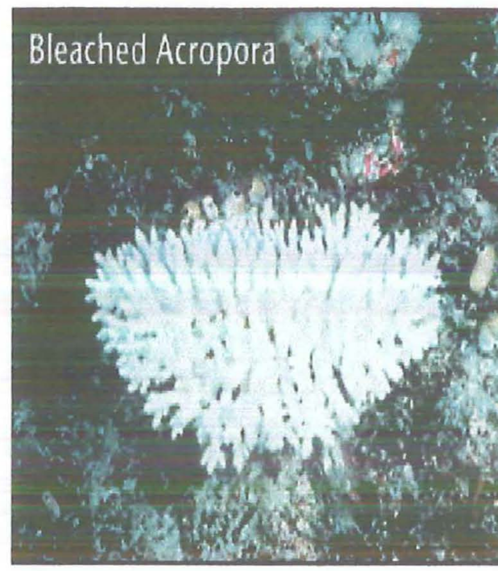

Figure 1.2b - A typical patch of dead or 'bleached' coral.

Courtesy of IUCN (2000).

The coral species *Pocillopera damicornis,* in particular, has been observed to have experienced detrimental 'bleaching' episodes over the past decade (B. Hutchins, pers. comm.), resulting in mass coral mortality at Rottnest Island (Table 1.1). There is some debate in the Western Australian scientific community, concerning whether this mortality is due to natural phenomena such as predation, temperature extremes, or currents, ENSO cycles, tidal movement, storm events, and sea level changes, or due to human-induced disturbance (SCUBA, 1998). However, as stated earlier, changes in SSTs, particularly degree heating weeks, have been shown to have large impacts on coral survival elsewhere and are currently considered amongst coral researchers to be a primary cause of coral mortality (IUCN, 2000). The use of remotely sensed SST data derived from the nearshore waters of Rottnest Island will help determine whether such coral bleaching episodes are thermally induced within the specified study region.

Table 1.1 Location and duration of coral bleaching events at Parker Point, Rottnest Island during the 1990s.

NB: Coral bleaching episodes at Rottnest Island have not been documented, and are based upon historical observations by B. Hutchins (B. Hutchins, pers. comm.).

Year	Month	Location
1995	May-August	Parker Point - moderate sized patches
1996	May August Dec	Upper surfaces in Parker Point Spread: Dyer Isl., Cape Vlamingh and Stark Bay Corals observed to be recovering.
1997	Most	Parker Point
1998	Jan-Mar June-Sept	Parker Point High coral mortality at Parker Point
1999	April	Parker Point, Waters 6-10m deep Recovery observed by June 1999.
2000	N/A	Only minor, isolated bleaching events
2001	N/A	Only minor, isolated bleaching events

1.5 Study Aims

This study is divided into three distinct components, based upon the main aim of assessing the ability of satellite remote sensing for determining sea surface temperatures in nearshore environments.

Component 1 - Satellite and Logger Data Comparisons

The first component aims to assess the accuracy of satellite SST data (derived in nearshore environments) by comparing data to *in situ* logger derived data for the period May-September 2001. In order to ensure that the analysis yielded the most accurate results possible, algorithms (McMillin & Crosby vs. MCSST) used by the NOAA / AVHRR satellite, were evaluated to determine which was the most accurate satellite algorithm to use in comparisons with *in situ* loggers.

Component 2 - Spatial & Temporal Comparisons

Spatial SST variability was examined in order to discover existing differences between locations (Parker Point, Thomson's Bay and Geordie Bay), and temperature divergence with distance from the coast (offshore vs. nearshore logger data). This involved the construction of a climatology for the nearshore regions of Parker Point, Thomson's Bay and Geordie Bay. This spatial SST variability has not been examined by previous researchers and is fundamental to the management of Rottnest's marine environment.

Component 3 -Application of Remotely Sensed Nearshore SSTs

These findings were amalgamated, and satellite-derived SST data from a period of 7 years were utilised, in an attempt to examine the nearshore climatology for Rottnest Island. As an example of the use of satellite-derived SST to coastal environmental issues, the relationship between nearshore coral bleaching episodes and periods of elevated temperatures or degree heating weeks has been examined.

CHAPTER 2.0

METHODS & MATERIALS

2.1 Study Description

The nearshore waters of five sites at Rottnest Island, Western Australia, namely Parker Point nearshore (PPI), Thomson's Bay nearshore (TBI) and offshore (TBO), and Geordie Bay nearshore (GBI) and offshore (GBO) were fitted with *in situ* temperature loggers between May-September 2001. These data were compared with remotely sensed data in order to establish the ability of satellites to extract SST data in nearshore environments, the principle aim of this study. In addition satellite algorithms, spatial and temporal variance, and management applications (coral bleaching) were examined.

2.2 Study Site Location

The sites were chosen based upon the geomorphological and environmental conditions such as depth and distance from the shore, ocean mixing, flushing, circulation, and tidal movement (Table 2.1, Figure 2.1). Site characteristics were optimally such that loggers could be fastened and retrieved with ease, were well flushed and mixed, were not too treacherous or hazardous for logger deployment and retrieval, were within 1km of the coast for nearshore sites, and outside 1km of the coast for offshore sites, and were representative of the surrounding marine environment. Three of the *in situ* sites were located in nearshore waters (within 1 km of the coast), and a further three sites were located in more offshore waters (>1km from shore). The loggers were placed either near the surface attached to a float, or mounted on the seabed (Table 2.1. 2.4a and b), however, the depth varies at most by 1m between sites, and due to the well-mixed characteristics of the marine environment in these locations, this depth variation does not affect the results. Parker Point is often affected by high incidences of flushing and mixing, as is Thomson's Bay, with Geordie Bay being more protected (Hopkin, 2001). Bathymetry also varies around the island (Figure 2.1), with nearshore and offshore sites in Thomson's Bay being shallower than the sites at Parker Point and Geordie Bay (summarised in Table 2.1).

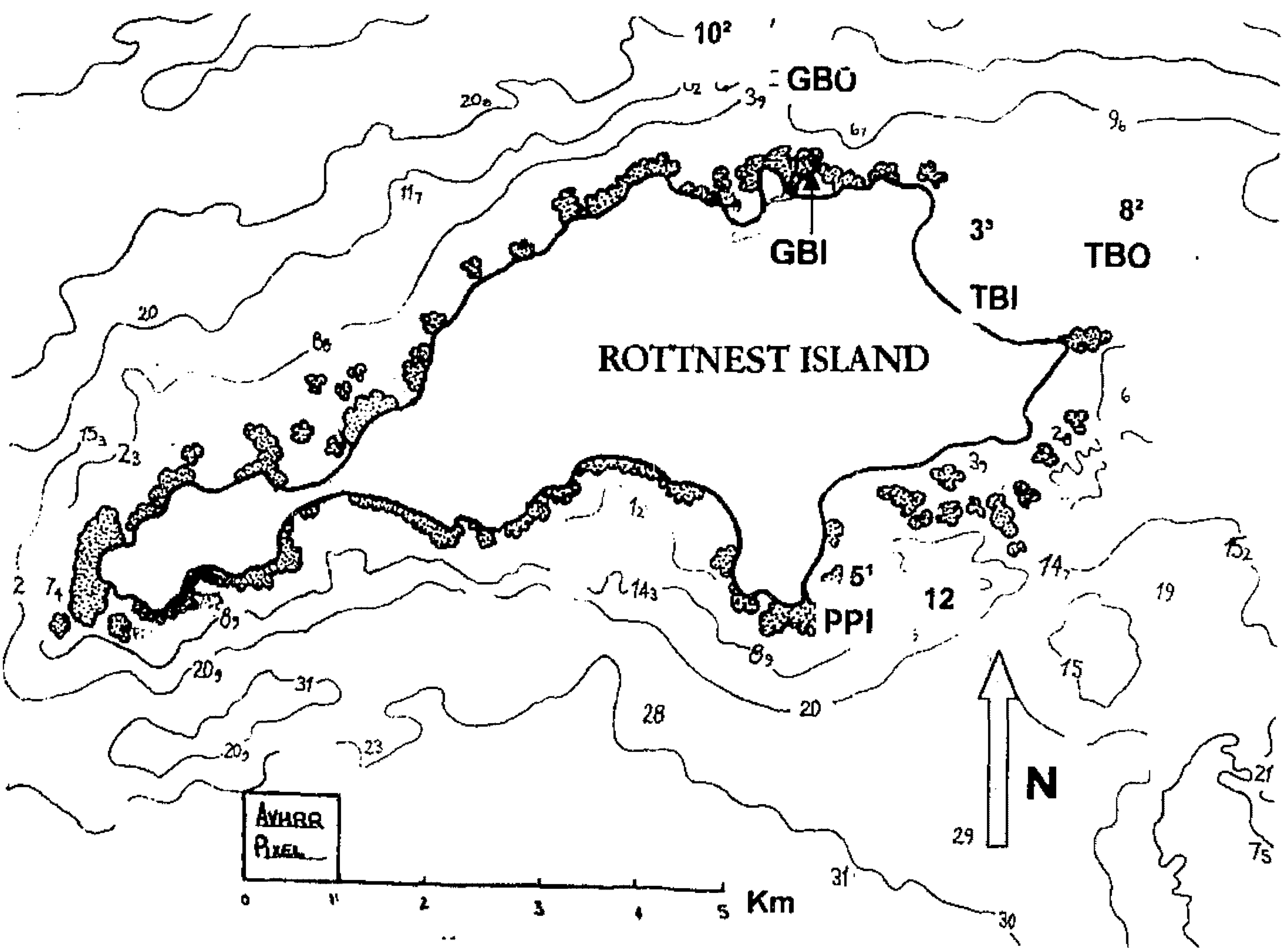

Figure 2.1 – Bathymetric Map of the specified study region, Rottnest Island, illustrating location of *in situ* temperature loggers at Parker Point (PPI), Thomson's Bay (TBI and TBO) and Geordie Bay (GBI and GBO), and relative size of AVHRR satellite pixels. It should be noted that location of satellite pixels is subject to change with each satellite orbit. Numbers represent bathymetry in metres.

Table 2.1 Logger Sites at Rottnest Island, WA.

Site	Location	Mounting	Environment & Conditions
PPI	Parker Point Inshore 32°01'490"S, 115°31'903"E	Metal anchor plate, 1.3m below surface	Nearshore, well-mixed tropical coral (*Pocillopora damicornis)* reef environment.
TBI	Thomson's Bay Inshore 31°59'900"S, 115°32'940"E	Mooring buoy, 0.3m below surface	Well-flushed bay, limited seagrass communities. High anthropogenic usage zone.
TBO	Thomson's Bay Offshore 32°59'456"S, 115°32'348"E	Cardinal Marker, 1.3 m below surface	Open ocean marine sanctuary zone containing some reef and seagrasses.
GBI	Geordie Bay Inshore 32°59'400"S, 115°31'310"E	Mooring buoy, 0.3m below surface	Nearshore sheltered bay. Presence of *Cyphastrea serailia* coral.
GBO	Geordie Bay Offshore 32°59'456"S, 115°31'348"E	Starboard Marker, 1.3m below surface	Open ocean location with sparse corals, little other sea-flora.

2.3 In Situ Temperature Measurements

In situ SSTs were recorded at each site (Figure 2.1) using Onset's™ TidbiT® optic temperature loggers (Figure 2.2), which record temperatures between -20 °C and +50 °C to an accuracy of 0.2 °C. The loggers were attached via cable ties to mooring chains at each site, with the exception of the inshore at Parker Point where the loggers were cable-tied to a post-card sized metal plate, which was then secured to the shallow reef using tent pegs (Figure 2.4b).

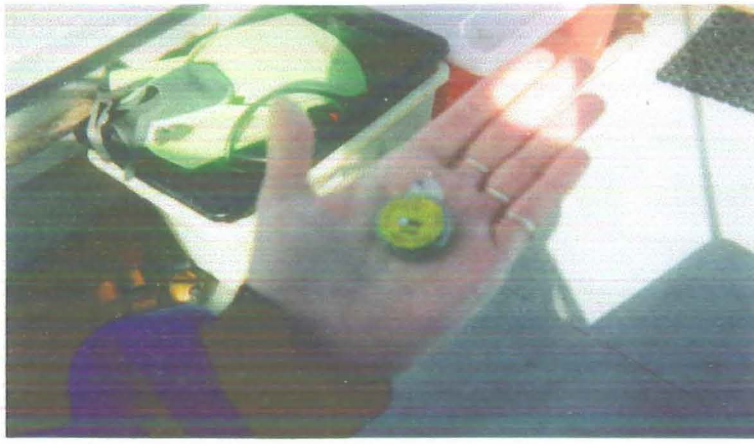

Figure 2.2 TidbiT® optic SST loggers, which were deployed at five sites around Rottnest Island between May-September 2001.

Logger-derived data were obtained for comparisons with satellite data for the study period between May and September 2001 (Figure 2.3).

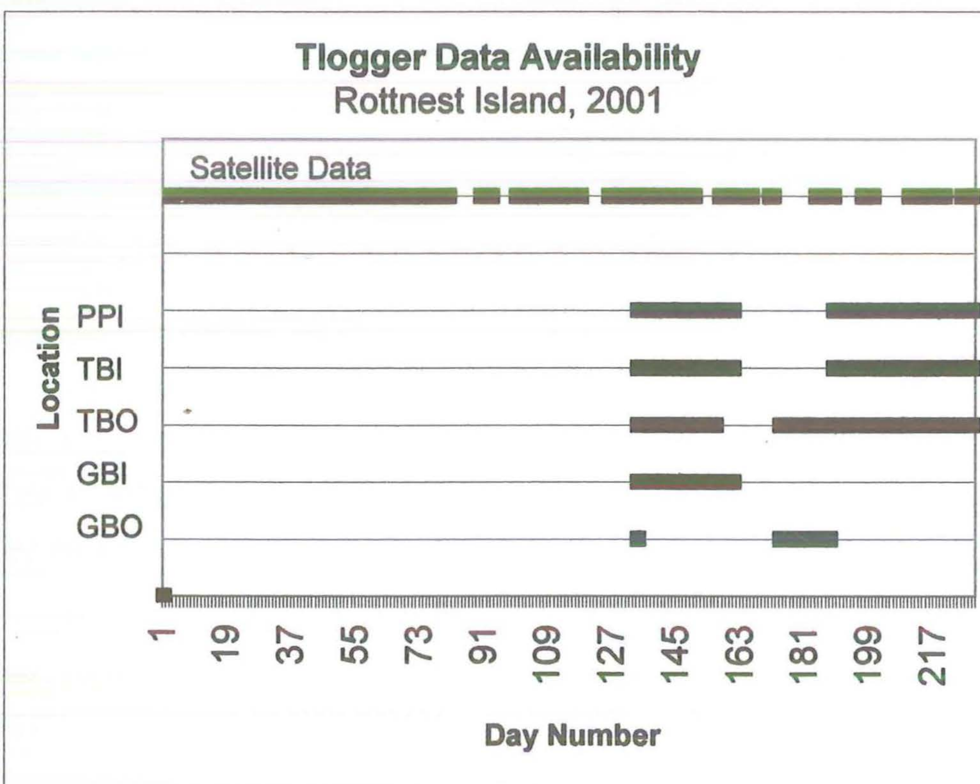

Figure 2.3 - Periods and location of temperature logger deployments. Gaps are due to vandalism and/or removal of loggers. Vandalism resulted in no logger-derived data available for the offshore site at Parker Point.

2.3.1 Calibrating Logger

To calibrate the loggers, each logger was firstly triggered and then placed in a tank of water at room temperature. A small pump was installed in the tank to mix the water to ensure uniform temperature throughout the tank. The tank water was then gradually warmed by adding hot water. Manual readings with a SIS™ RTM4002X® stable platinum sensor thermometer, with an accuracy of ±0.003°C and resolution of ±0.001°C, were taken at 10-minute intervals to calibrate the loggers. Once water temperature had reached about 31°C, ice was added and the water cooled to 13°C. These maximum and minimum calibration levels were selected to reflect the extreme temperatures these loggers would be recording in the study region. Upon completion of the calibration, it was found that the temperature loggers were in very close coherence with manual thermometer readings, and thus no modifications were made to the logger results based upon the results of the calibration, however, as stated, degrees of logger accuracy and resolution were dually noted.

2.3.2 Logger Set Up & Deployment

The loggers were set up and triggered via computer, Base-Station®, and Onset's™ Boxcar Pro program. It was found that SCUBA was not required for deployment, and that snorkelling was sufficient. Loggers were set up to record SST measurements once every fifteen minutes, with the ability to store the data for 388 days. Logger deployment, although varied, occurred approximately once every 6 weeks.

Figure 2.4a Surface floats used to attach loggers, via cable ties, to.

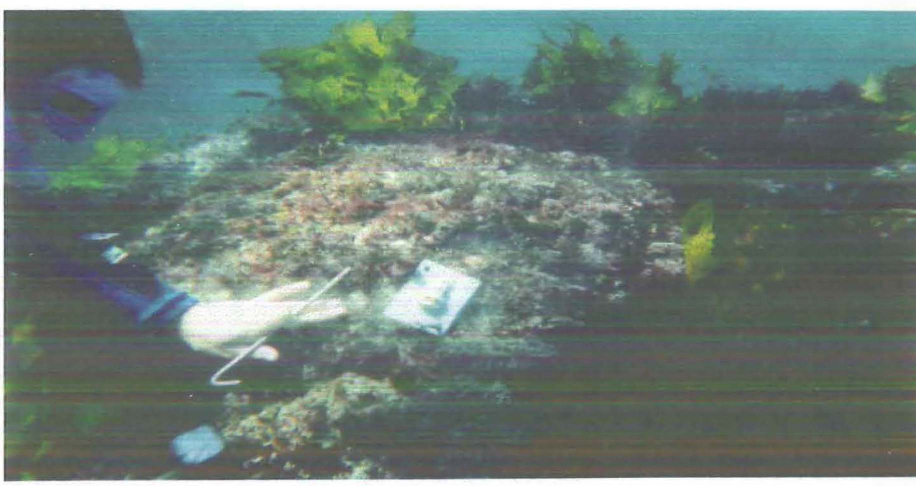

Figure 2.4b Logger fastening via anchorage to reef system.

2.3.3 Recovery and Data Retrieval

Logger retrieval and re-deployment occurred approximately once every 6 weeks in order to allow for data retrieval and analysis. Retrieved loggers were replaced with newly calibrated loggers. Upon retrieval by snorkelling, periphyton growth was cleaned from the face of the each logger, using a damp warm cloth to ensure clear transmission of data. Once cleaned, data were acquired from the loggers via a down-link cable and Optic Base Station® to the computer.

2.3.3 Summary of Logger Data Processing & Analysis

This description is a brief summary only, for detailed information on logger data processing, please refer to Figure 2.5.

Once calibrated, set up and deployed, loggers are recovered from field, as specified previously in this chapter, they are processed as per the following steps:

1. Loggers connected to computer via Optic Base Station® and interface cable;
2. Software program Boxcar Pro® download data into one large file containing SST measurements taken every 15 minutes;
3. Computer program is run in order to extract hourly data averages for each site;
4. Data generated are analysed and manipulated as per Chapter 3.0.

Logger Data Extraction Process (May-September 2001)

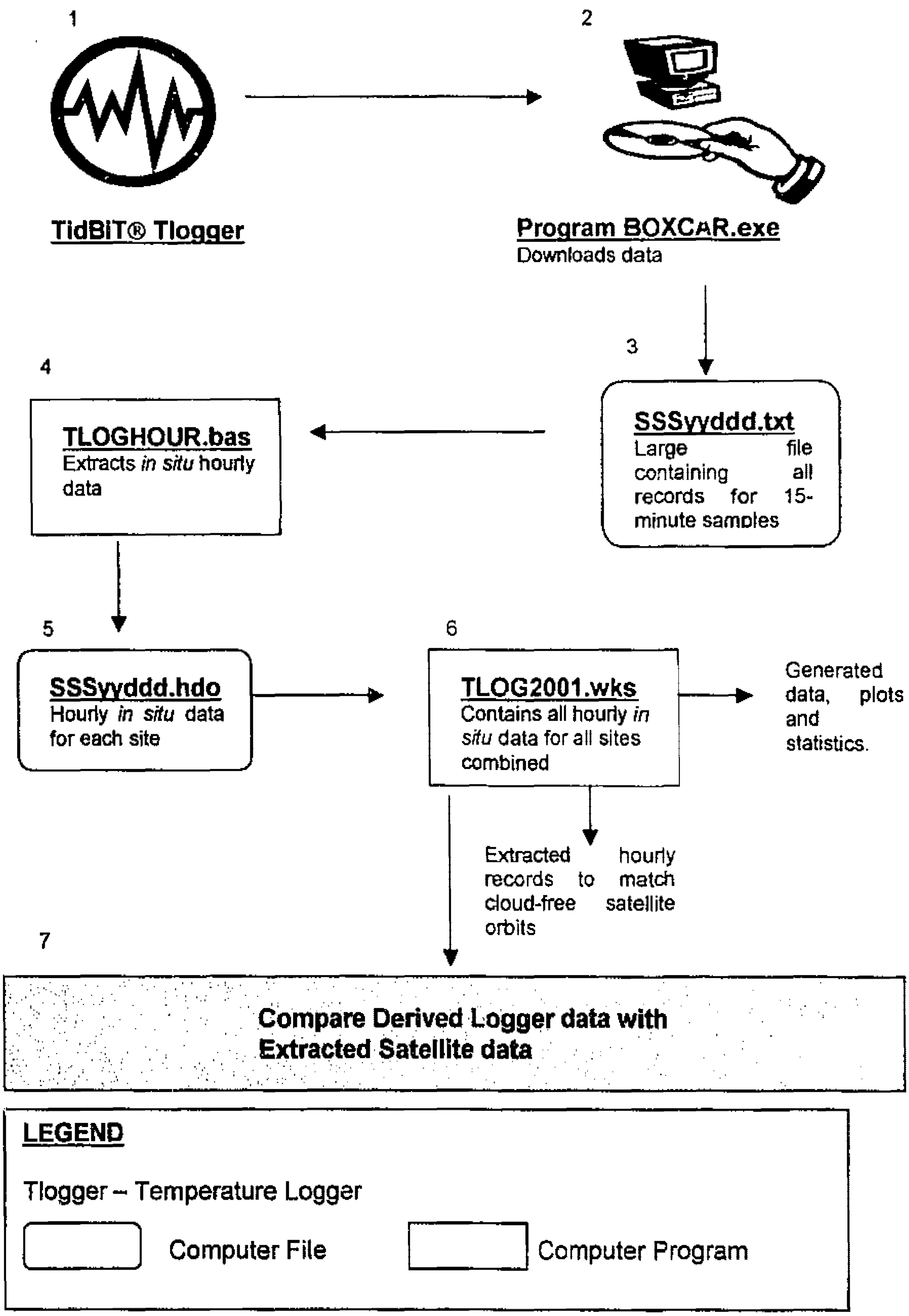

Figure 2.5 – Logger Data Extraction Process (May-September 2001)

2.4 Satellite Data Retrieval

2.4.1 NOAA/AVHRR Satellite Data

Satellite derived sea surface temperature data used in the present study were received from the NOAA/AVHRR-satellite. As the visible data were required for manual geolocation of the study-sites, the night-passes, and cloudy data could not be utilised. It was also discovered that sun-glint affected SST results for a small number of days and these data were also omitted. Sun-glint occurs when the sun is reflected into the satellite's sensors and may corrupt the SST readings (Pearce, pers. comm.).

Historical NOAA/AVHRR data were obtained for the years 1995-2001. This period was chosen to encapsulate observed coral bleaching episodes (Figure 2.6).

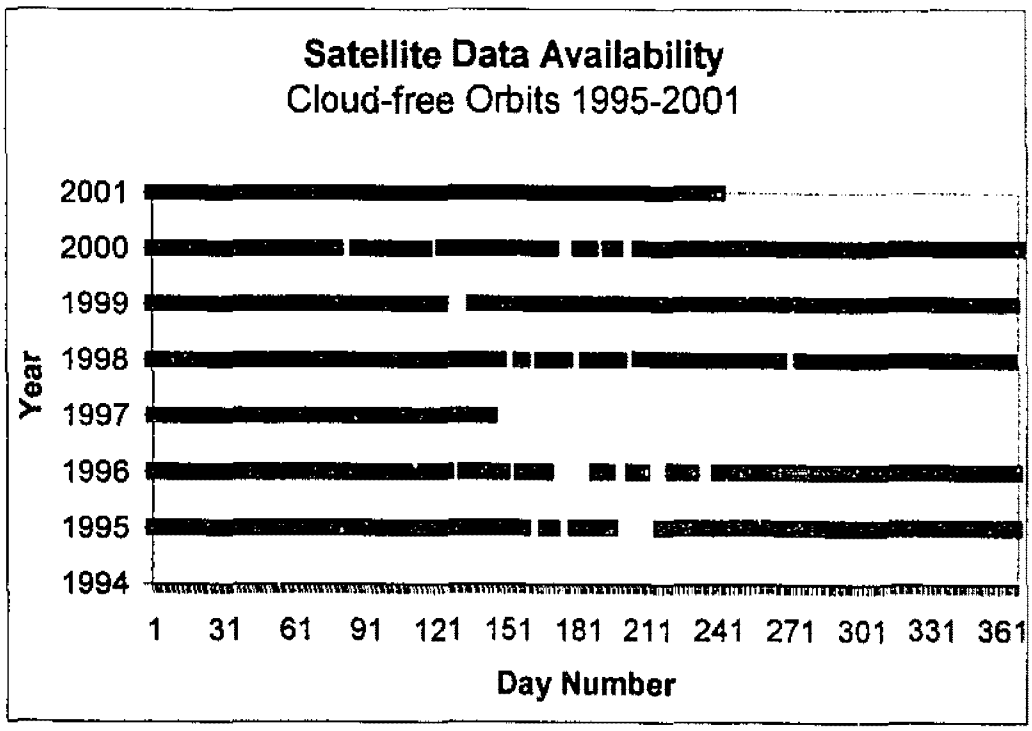

Figure 2.6 - Diagram showing the periods for which cloud-free satellite passes were obtained between 1995 and mid 2001.

Satellite derived data affected by atmospheric influences such as cloud cover and sun-glint, result in the data gaps (Figure 2.6) (Prof. M. Lynch, pers. comm.).

The satellite data were obtained from the Department of Land Administration (DOLA) and the Western Australian Satellite Technology and Applications Consortium (WASTAC). The NOAA satellite measures the radiation in 5 bands of differing electromagnetic wavelengths in the visible and infrared spectral regions (Table 2.2). These data are essentially 'non interpretable' and must undergo processing, cloud/sun-glint screening and manipulation in order to attain quantitative and qualitative data. This process involved the construction of specialised computer programs designed by Pearce and Faskel and a complex manual process to derive nearshore site-specific remotely sensed SST data (Figure 2.8). Once data were formatted into a useable form, they were then required to be manually sorted, in order to obtain site-specific sea surface temperature data. Processing time required one week per year of satellite data. This individualised data processing was required as each satellite orbit shifts slightly in location and timing. If this shift did not occur, it would have been possible to extract SSTs at the selected sites by simply running a generic computer program, which would be able to select open-ocean pixels. In a nearshore environment however, the threat of land-contaminated data exists, and thus 'clean' pixels close to the coast (and as close to pertaining *in situ* devices if applicable) must still be hand-selected. Manual sorting, making differentiations between land and water, allows for the nearest 'clean' (non-land polluted) pixel to be selected from the data (Figures 2.1 and 2.7). The pixel that most closely represents the chosen study site, as close to the shore as possible, was selected for each cloud-free and sun-glint-free orbit, measured using two satellite algorithms, McMillin & Crosby (Band 3), and MCSST (Band 6).

Table 2.2 Explanation of measurements from each AVHRR "band" in µNOAA format (see also - Figure 2.7)

[illegible]	[illegible]
1	Visible band (checks for cloud and land)
2	Near Infra Red (checks for cloud and land)
3	Derived SST using McMillin & Crosby algorithm
4	Brightness temperature
5	Brightness temperature
6	Derived SST using MCSST algorithm (N14 and N16 only)

Bands 3 and 6 contain the sea surface temperature values, in 1.1km x 1.1km pixel (or cell) form (Figure 2.7).

Satellite Pixel Data Manual Extraction Example.

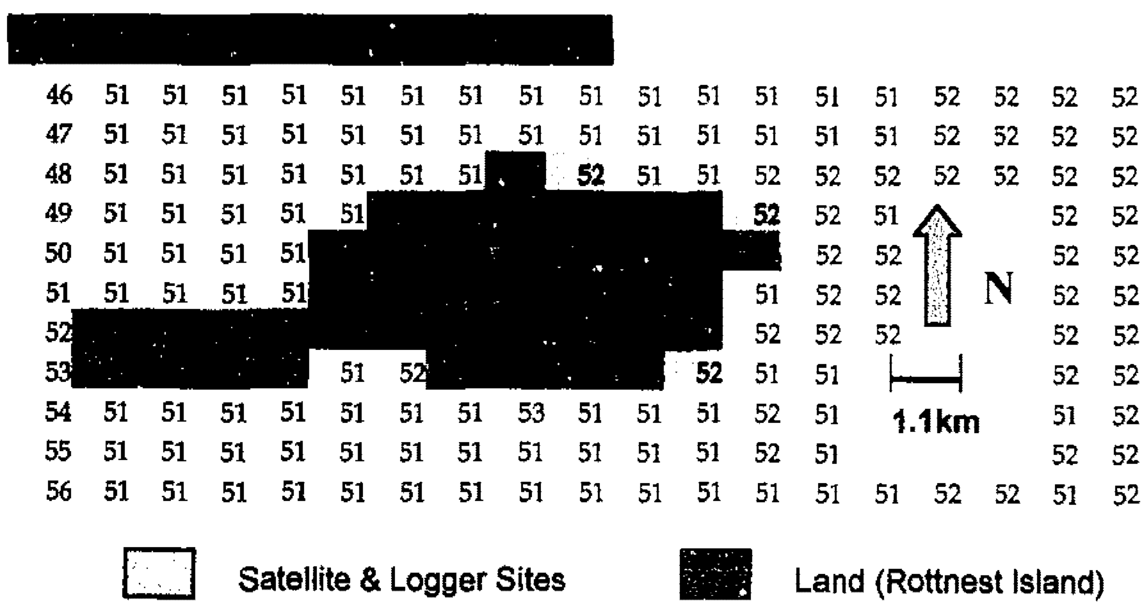

Figure 2.7 – An example of satellite band 2 (near infrared) data for each 1.1 x 1.1km pixel used to select nearshore pixels corresponding to the sample sites. The shape of the land of Rottnest Island is shown by the shaded pixels that indicate a rise in reflectance values.

By manually selecting non land-contaminated pixels (clean pixels) as close to the coast as possible, it is found that these pixels were often greater than 1.1km (size of each satellite pixel) from the coast.

2.4.2 Summary of Satellite Data Processing & Analysis

This description is a brief summary only, for detailed information on satellite data processing, please refer to Figure 2.8.

1. WASTAC obtain NOAA / AVHRR satellite data in μNOAA format (see step 5, Figure 2.8);
2. Computer program is run in order to extract SSTs in usable format;
3. A further program is run in order to extract the region of Rottnest Island from the satellite data;
4. Upon identification of the Rottnest mainland, the pixels ($1.1km^2$), corresponding to the selected study sites, are manually selected;
5. Cloud and data screening methods are employed, and data analysis is carried out as per section and Chapter 3.0 – Results.

2.5 Data Analysis

- Component 1 – Satellite and Logger Data Comparisons

In situ readings were obtained using temperature loggers. These data were then compared with NOAA/AVHRR data in order to evaluate the accuracy of the use of satellite remote sensing to determine sea surface temperatures in nearshore environments. In addition, the algorithms used by the NOAA/AVHRR satellite to determine SSTs (McMillin & Crosby vs. MCSST) were compared in order to establish the biases involved with these data, and thus the degree of accuracy of SST readings.

Both satellite and logger comparisons and the McMillin & Crosby vs. MCSST comparisons were made largely in Microsoft Excel, with formulae calculating bias, root mean square difference (RMS) and correlation. It should be noted that the bias is calculated by subtracting the mean temperature logger values from the mean satellite data values. Correlation co-efficient calculation is an automated features of Microsoft Excel. Frequency distributions are obtained by subtracting mean offshore / nearshore logger derived data from mean satellite derived data, and grouping these differences into bin-arrays or categories (i.e. 0 - 0.25°C). Graphing these results indicated any outliers, the degree of difference that exists between the data, and the frequency of which these differences have occurred.

- Component 2 - Spatial & Temporal Investigations & Climatology

Spatial SST variability will be examined in order to discover existing differences between locations (Parker Point, Thomson's Bay and Geordie Bay), and temperature divergence with distance from the coast (offshore vs. nearshore logger data). This will involve the construction of a mean climatology, utilising data for the period 1995-2001, for the nearshore regions of Parker Point, Thomson's Bay and Geordie Bay.

As satellite day-passes may only be utilised, logger derived data are required in order to create a diel (24 hour) temperature profile for all sites at Rottnest Island. Diel temperature anomalies are derived by subtracting the total mean of the logger-derived data, from individual logger data values, and plotting the differences. Plotting the anomalies solves the problems associated with data gaps (which may occur due to cloud cover, sun-glint, skipped orbits, or land contamination) by presenting the average relationship of the differences between logger-derived data. It is necessary to display results as anomalies as these give a clear indication of difference in temperature ranges between the sites.

Nearshore climatology construction is facilitated by the extraction of satellite data as close to the coast as possible in each Parker Point, Thomson's Bay and

Geordie Bay. This requires the satellite data extraction method as illustrated in Figure 2.8. Satellite data for each site are averaged for the period 1995-2001 in order to generate mean monthly SST's.

- Component 3 - Application of Remotely Sensed Nearshore SST's

In conclusion, the previous findings were applied to a management issue, by utilising mean nearshore satellite-derived SST data from a period of 7 years, to examine the relationship between nearshore coral bleaching episodes and SSTs at Parker Point.

As determined by Wellington *et. Al.*, (2001), coral bleaching will generally occur when temperatures exceed 28°C for a period of over one week. This week of elevated temperatures is termed a degree-heating week (DHW) (IUCN, 2000; Wellington *et al.*, 2001). The present study however takes into account the fact that Rottnest Island is the most southerly location for coral colonisation. As waters around Rottnest Island rarely reach 28 °C, it is assumed that the corals have indeed acclimatised to the cooler SSTs experienced in this region. For this reason, the mean maximum temperature has been specifically calculated for Rottnest Island by averaging mean maximum summertime temperatures (for the 7 year period), specified at 22.7°C. This study has introduced a new term, a degree-cooling week (DCW), which has been devised in relation again to the fact that tropical corals do not grow at any more southerly locations, suggesting that minimal temperature could be a threshold for coral colonisation. This in effect is the opposite of a degree-heating week, where temperatures are 1 °C below the average minimum SST (namely 18.4 °C) for over one week. Degree-cooling week periods are obtained by calculating averages of minimum wintertime temperatures over the seven-year period. Both of these phenomena are examined.

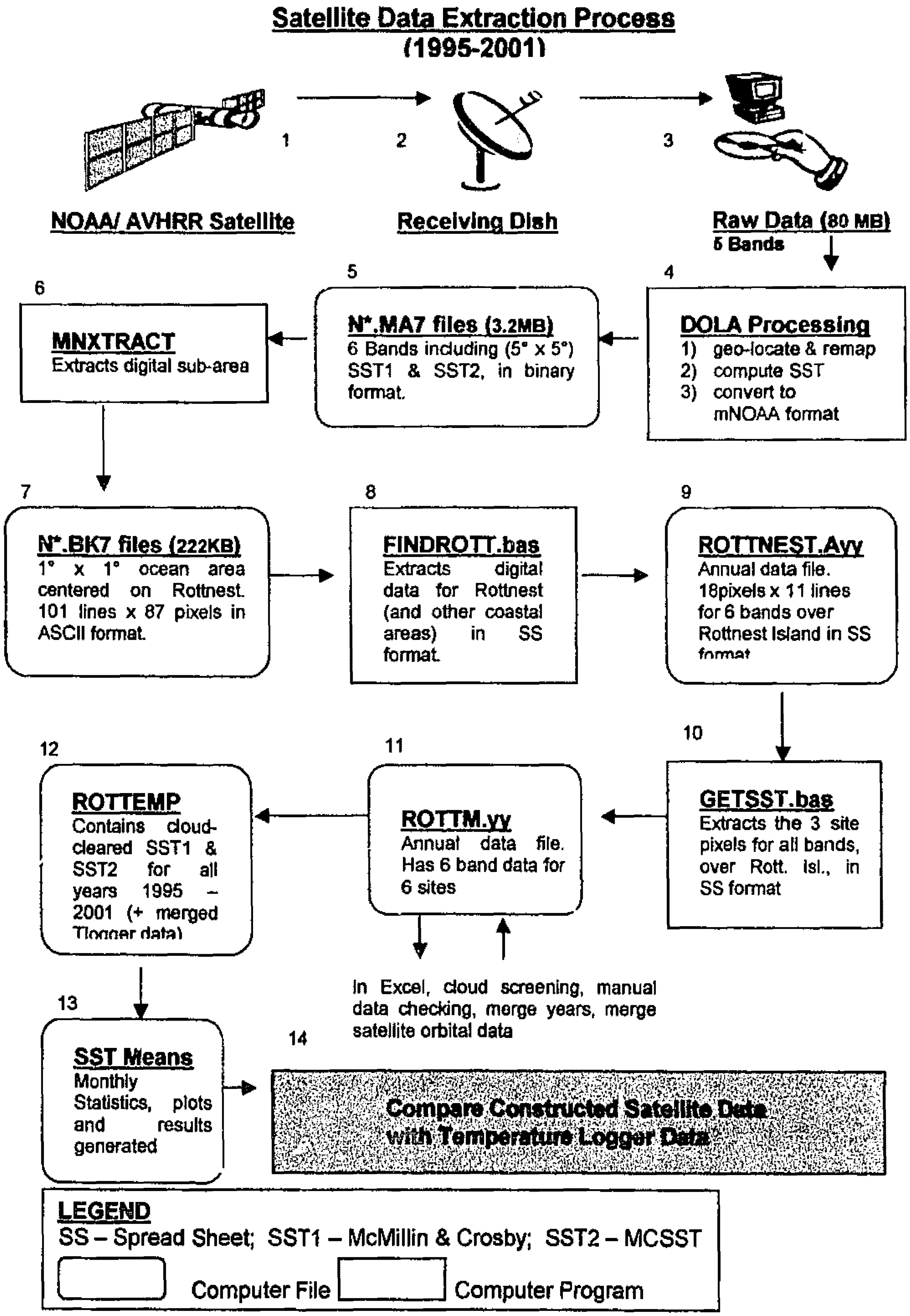

Figure 2.8 - Satellite Data Extraction Flow-chart

2.5.1 Satellite Data Restrictions and Requirements

Retrieval of temperature data was restricted to cloud-free days, as clouds affect the SST measurements by in effect reading the 'cloud' temperature and not the skin sea surface temperature (Table 2.2). It became evident during the study that cloud determination is difficult and the following cloud-screening rules were employed:

1. Absolute threshold test: delete all SST's where temperatures were: <15°C in summer and <12°C in winter, and any temperatures >30°C (Pearce, *et al.*, 1999);
2. Spatial variability test: delete all SSTs where the range of brightness temperatures in band 4, in a 4 pixel block, at each site exceeded 1°C:
3. In some cases, the colour SST images (photos) were viewed in order to confirm if cloud was present.
4. Where physical thermal images showed evidence of sun-glint, data were also erased from the database. It became evident that sun-glint affected results, although liaison with WA's remote sensing specialists could find no reason for this effect (M. Lynch, pers. comm.), and is a significant finding in need of further future research.

CHAPTER 3.0
RESULTS

Satellite and logger-derived data were examined in order to attain the feasibility of using satellite remote sensing, to obtain SST's in nearshore environments, the principal aim of the study. Evaluation involved examining the data via the methods outlined below, to address each of the three study components:

3.1 Component 1 - Satellite Data Assessment Results

3.1.1 Algorithm Analysis

The temperature values derived from the McMillin & Crosby and MCSST satellite algorithms were compared to determine which was the most accurate algorithm for comparisons with *in situ* data.

By plotting the MCSST algorithm against the McMillin & Crosby algorithm, a clear indication of the relationship between the two algorithms is obtained (Figure 3.1). SSTs derived from McMillin & Crosby were generally higher than those from MCSST, which is shown by the majority of points lying below and to the right of the line (slope of the line is 1.0).

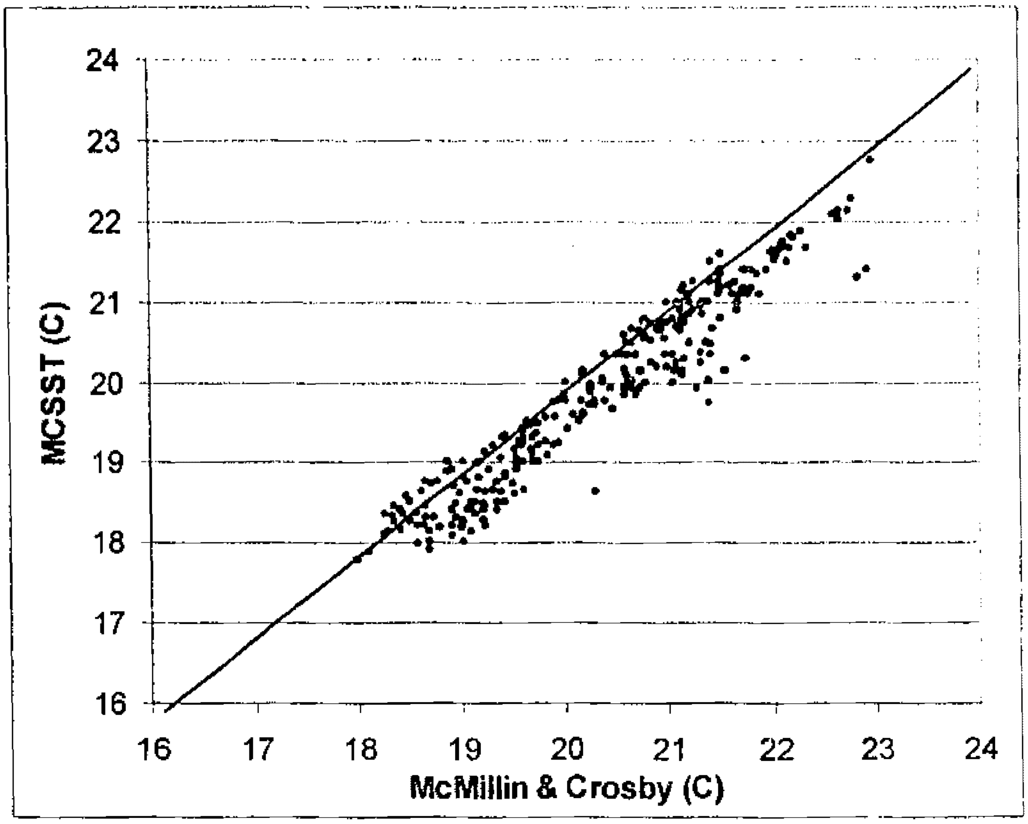

Figure 3.1 - Comparison of MCSST and McMillin & Crosby algorithms for all 3 sites, for the period 1995-2001. Line indicates a slope of 1.0, which would be the relationship if total agreement existed between the two algorithms.

As Figure 3.1 only gives an indication as to the difference between the two algorithms, the bias of each algorithm was then calculated by subtracting mean logger-derived data from mean satellite-derived data. In addition the standard deviation, in the form of root mean square (RMS) difference (Pearce, *et al.*, 1989), and the correlation co-efficient were calculated (Table 3.1). The equation for the calculation of RMS is given as:

$$\mathrm{RMS} = \sqrt{\frac{\sum (\mathrm{Tsatellite} - \mathrm{Tlogger})^2}{N}}$$

In both nearshore and offshore waters, the MCSST algorithm produced a lower bias than the McMillin & Crosby algorithm, with temperatures being over or underestimated by < 0.1°C by the former algorithm, but overestimated by about 0.5°C by the latter algorithm (Table 3.1).

Furthermore, the MCSST algorithm exhibited lower variation (RMS) and higher correlation co-efficient than McMillin & Crosby.

Table 3.1 - Comparison of McMillin & Crosby and MCSST algorithms against logger-derived data, utilising bias, root mean square difference and correlation coefficient.

Bias = Mean satellite data - mean logger data
CC = Correlation Co-efficient RMS = Root-Mean-Square
No. = Number of observations McM&Cr = McMillin & Crosby

	Temperature Logger Data							
Satellite Data	**Offshore**				**Inshore**			
Algorithm	**Bias**	**RMS**	**CC**	**No.**	**Bias**	**RMS**	**CC**	**No.**
McM&Cr	-0.459	0.714	0.913	45	-0.552	1.039	0.725	69
MCSST	0.086	0.462	0.930	45	-0.042	0.855	0.811	69

The frequency distributions of the temperature differences between the two algorithms and the loggers (Figure 3.2 a, b) confirm earlier findings that the 'error' associated with the MCSST is smaller than those from the McMillin & Crosby algorithm. The greatest differences between satellite and *in situ* SSTs for the MCSST algorithm fell between 0 to 0.19°C (27%), with 50% of temperatures differing by only -0.25 to 0.25 °C (Figure 3.2a). Furthermore, MCSST temperatures differed by only ± 0.5°C approximately 60% of the time, or ± 0.75°C approximately 90% of the time. In comparison with MCSST, only 20% of the SSTs derived from the McMillin & Crosby algorithm were between -0.25 and 0.25 °C of the *in situ* loggers, while 39% of the values were 0.25 - 0.75 °C greater than SSTs determined from *in situ* loggers (Figure 3.2b). In this case it was noted that only 40% of the time, McMillin & Crosby SST values differed from *in situ* data by between ± 0.5 °C, (or by ± 1.5°C approximately 90% of the time), a less favourable result than that found with MCSST.

3.1.2 Correspondence Test Results

As *in situ* data were derived from both nearshore and offshore locations, investigations were made in order to determine the correspondence of the satellite data with spatial variance in logger data.

Satellite and *in situ* data comparisons were facilitated via the calculation of regression line values (R^2) and slope. Such results may be plotted in scatter-graph format, however due to data gaps experienced, this representation was not available. The desired result would be for all points to fall alongside the regression line (R^2), and for the angle of the slope to yield a value as close to 1.0 as possible. Analysis showed that for the MCSST algorithm, the R^2 values were 0.918, with a slope of 0.94, compared with 0.91 and 0.92 for McMillin & Crosby, respectively. The relationship witnessed between the two algorithms indicated that they are of similar accuracy, however the MCSST is shown to be the more favourable algorithm.

Since the above results indicate that the MCSST algorithm yields a lower bias and variation, and higher correlation with *in situ* data, this algorithm will be used in the remaining sections of this study. Satellite data will also generally be compared with offshore logger data due to the higher degree of correlation (Table 3.1).

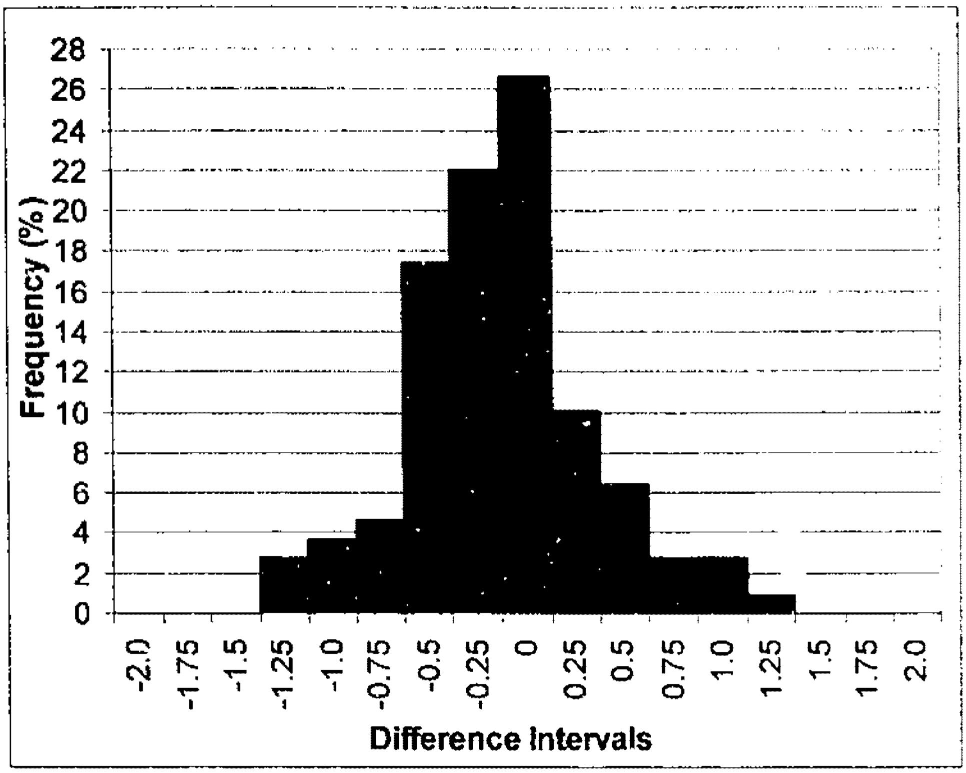

Figure 3.2 (a) – Frequency distribution of the differences between the MCSST algorithm and the offshore logger-derived data (May-September 2001),

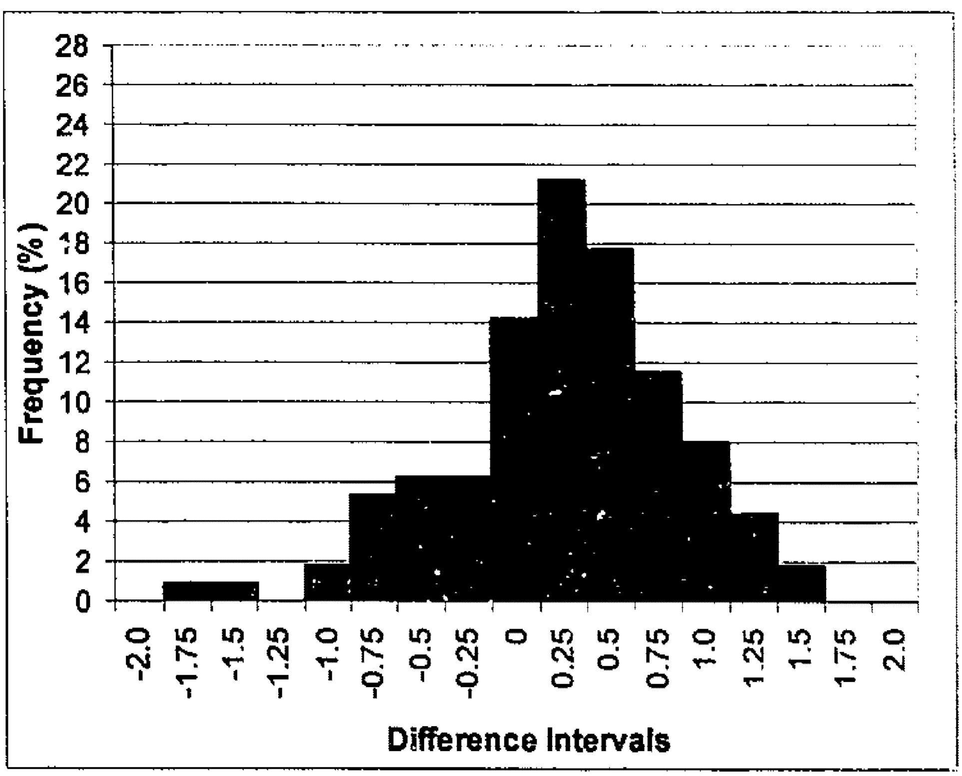

Figure 3.2 (b) – Frequency distribution of the differences between the McMillin & Crosby algorithm and the offshore logger-derived data (May-September 2001),

3.2 Component 2 – Spatial & Temporal Comparisons

Upon determination that satellite data matches most closely with offshore logger data (at least 1km from the coast), spatial SST variability, using the satellite data and offshore logger data, was examined in order to discover existing differences between locations (Parker Point, Thomson's Bay and Geordie Bay), and temperature divergence with distance from the coast (offshore vs. nearshore logger data).

Spatial comparisons have been made using seven years (1995-2001) of satellite data, using the more accurate MCSST algorithm, in order to examine spatial and temporal trends in nearshore SSTs. Temperature trends were distinctly annual, with warm summers and significantly cooler winters. Mean temperatures at Rottnest Island range from approximately 18.5°C in winter to about 22.7°C in summer. Two prominent depressions in winter temperatures can be witnessed in the winters of 1995 and 2000, with a prominent elevation in temperatures witnessed in the summer of 1999 (Figure 3.3). Of the seven-year period examined, a trend in mean annual temperatures is witnessed, with cooler summer temperatures (1995, 1998, and 2001), followed by two years of increased summer temperature (1996, 1997, 1999 and 2000), (Figure 3.3). The winter SSTs were similar over the seven-year period, with slightly lower temperatures experienced in 2000 and 2001.

Mean monthly satellite-derived data reveal minimal temperature differentiation between the three sites examined at Rottnest Island (Figure 3.3). Mean temperatures varied among Thomson's Bay, Geordie Bay and Parker Point by only ± 0.2°C. Thomson's Bay, the shallowest of the sites, displayed the greatest variability, with temperatures exceeding the other site by 0.1°C in the summer and were 0.2°C lower than other sites in winter (Figure 3.4).

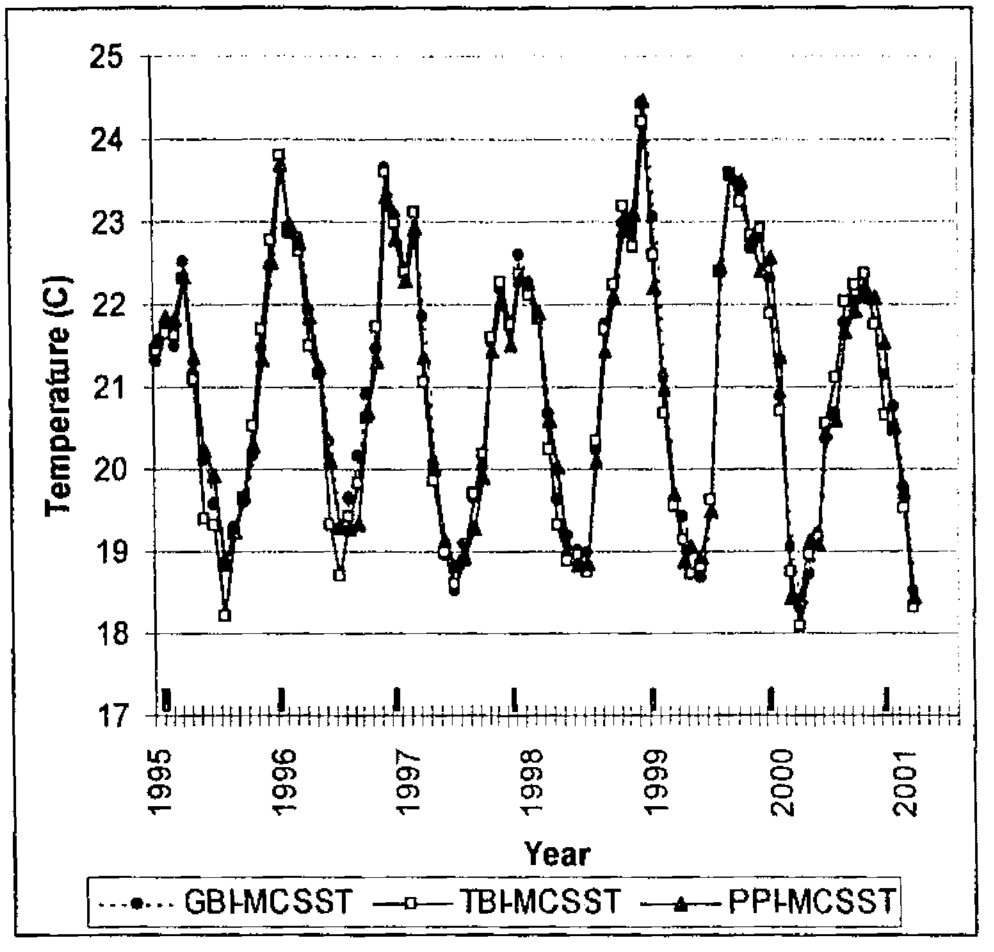

Figure 3.3 – Mean monthly satellite-derived sea surface temperatures approximately 1km from the coast at Parker Point (PP), Thomson's Bay (TB) and Geordie Bay (GB).

Climatological representation was achieved using mean monthly SST data over the seven year study period (Figure 3.4) This annual trend, indicates more clearly that temperatures for Thomson's Bay were generally lower in the winter, and warmer in the summer, than the other two sites (Figure 3.4).

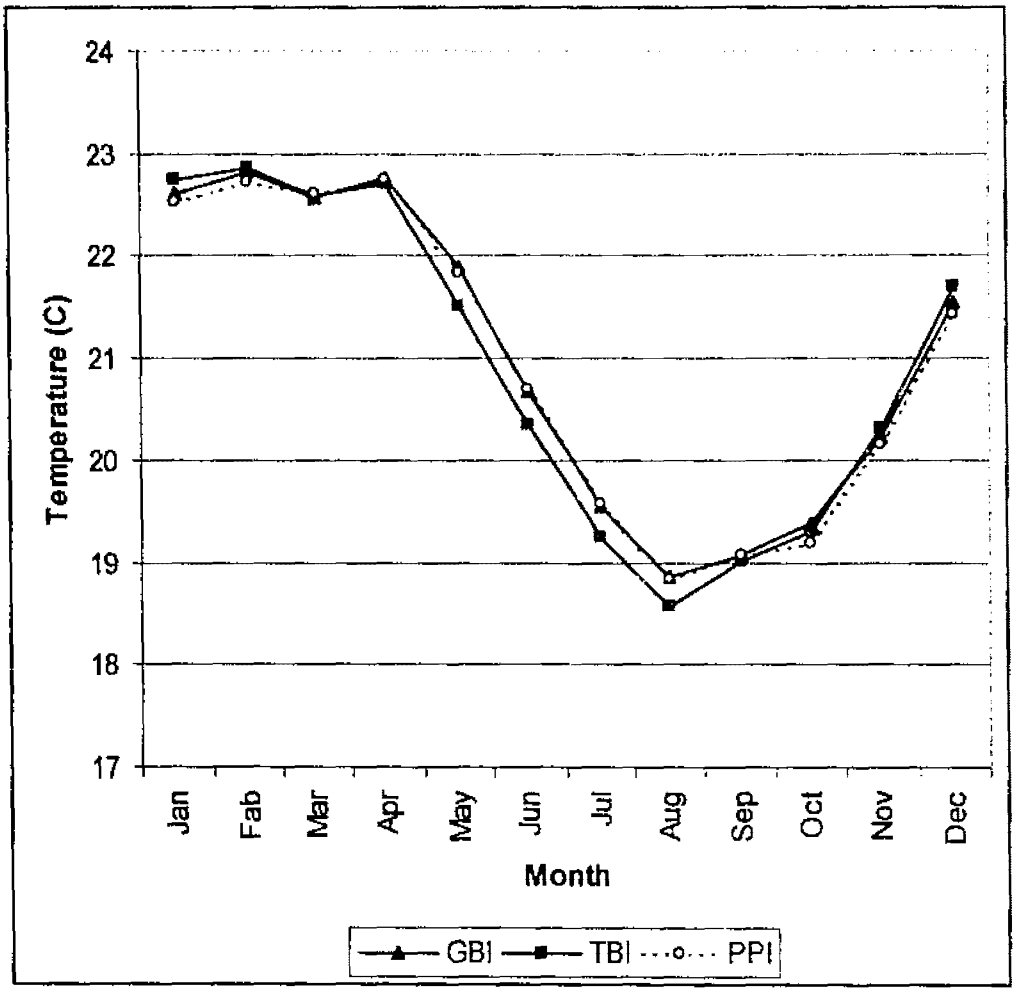

Figure 3.4 - Nearshore satellite-derived SST climatology for Parker Point (PP), Thomson's Bay (TB) and Geordie Bay (GB), at Rottnest Island, utilizing mean SST data for the period 1995-2001, derived from the MCSST algorithm.

Diel temperature cycles were used to facilitate hourly SST analysis (Figure 3.5). To examine diel (24 hour) temperature cycles, SST data from the loggers were used to calculate the mean (over the full data period) of the temperatures at each hourly interval, and then normalised by subtracting the long-term mean. Use of satellite data is not possible as the satellite passes over Rottnest Island only once per day, and thus diel patterns are not obtainable. It is clear that Thomson's Bay nearshore waters display the greatest temperature variance of any of the sites, although all nearshore sites show greater temperature anomalies than their offshore counterparts (Figure 3.5).

Sea surface temperatures are indicated to vary by <0.6°C over a daily cycle (Figure 3.5), with the highest mean temperature differences occurring at approximately 1500 hrs, with the greatest difference in temperatures approximately 0.2 °C between offshore Geordie Bay (GBO) and nearshore Thomson's Bay (TBI), the deepest and shallowest sites, respectively. The water is coolest at about 6-7am at all sites. No logger-derived data were available for offshore Parker Point.

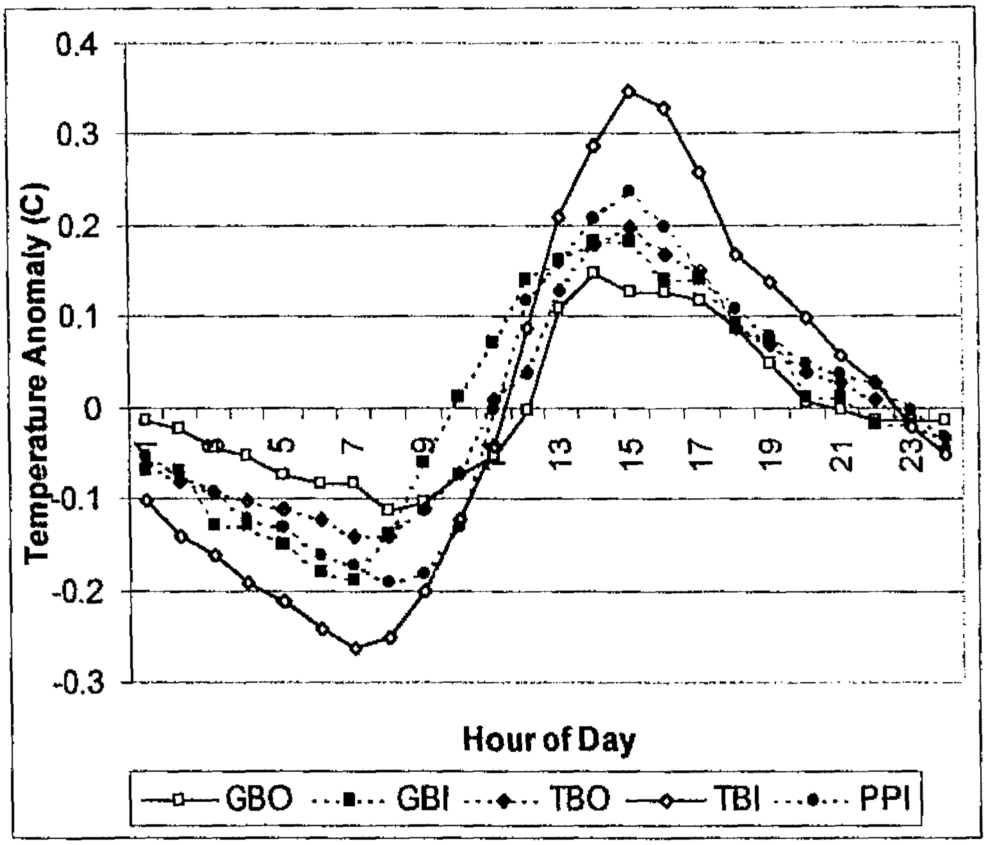

Figure 3.5 - Diel temperature pattern for nearshore and offshore Parker Point (PP), Thomson's Bay (TB) and Geordie Bay (GB) utilising *in situ* data for 2001.

Spatial comparisons of mean offshore *in situ* derived temperatures, and nearshore *in situ* derived temperatures are also made by comparing average SSTs in the diel cycle (Figure 3.5). Based upon these values, it can be seen that the nearshore sites display greater temperature variability than their offshore counterparts. At most, this difference can be seen to be approximately 0.1°C, based on anomaly values for Thomson's Bay.

3.3 Component 3 -Coral Bleaching/Temperature Relationship

Coral bleaching examination is facilitated by the use of degree-heating week thresholds as specified by IUCN, 2000, for the period 1995-2001. The coral bleaching episodes at Parker Point, Rottnest Island, are based upon observations by Dr. Barry Hutchins (Museum of Western Australia). Comparisons will be made between temperature thresholds, and coral mortality.

As tropical corals (dominated by *Pocillopera damicornis*) are found within the nearshore zone of Parker Point, the remotely sensed temperatures are compared with coral bleaching episodes at Parker Point between 1995-2001, as observed by Dr. Barry Hutchins (Museum of Western Australia). It should be noted that coral bleaching at Rottnest Island has not been documented in published literature, and results are based on observations only. Additional bleaching events may have occurred over this period, however there is no information relating to these events.

Should the universal DHW threshold be applied (28°C), temperatures at Parker Point never exceeded this value during the seven-year period. For this reason, a DHW, specifically for Parker Point, was calculated on the basis of the average maximum temperature. The average monthly minimum temperature at Parker Point was approximately 18.5 °C, with maximum mean SST of 22.7 °C. This means that an acclimatised degree-heating week (DHW) will occur where temperatures are elevated by 1 °C above 22.7 °C for over one week (as opposed to the universal threshold of 1°C above 28°C for over one week).

DHWs occurred during February/March of 1996 and 1999, during the last 3 weeks of April 1999, and during December/January of 2000 (Table 3.2). When these DHWs were compared with coral mortality observations (Figure 3.6), it is found that only 25% (or one incidence) of DHWs that occurred during 1995-2001 corresponded with coral bleaching events. This bleaching event was observed to have begun before the DHW occurred (Figure 3.6).

Bleaching was observed at varying times throughout the year, where both low and high temperatures occurred, and these bleaching episodes are seen to occur at varying duration (Figure 3.6).

For the purpose of this study, a new term, a degree-cooling week (DCW), has been introduced. This term refers to periods where temperatures are depressed by 1 °C below the mean minimum SST (namely 18.4 °C) for over one week. This lower SST threshold is examined as Parker Point is the southern most limit for the growth of tropical corals, and thus minimal temperature thresholds may influence the presence of these corals (Ward, 1994).

DCWs were found not to occur between 1995-2001, suggesting that temperatures rarely fall below the average wintertime minimum of 18.5°C.

Table 3.2 - Degree-heating weeks for the period 1995-2001, where temperatures exceed 22.7°C at Parker Point for over one week

Number of Weeks	Year	Day Number	Month
3	1996	43-65	Feb-Mar
1	1999	48-59	Feb-Mar
3	1999	93-120	Apr-May
2	1999-2000	363-13	Dec-Jan

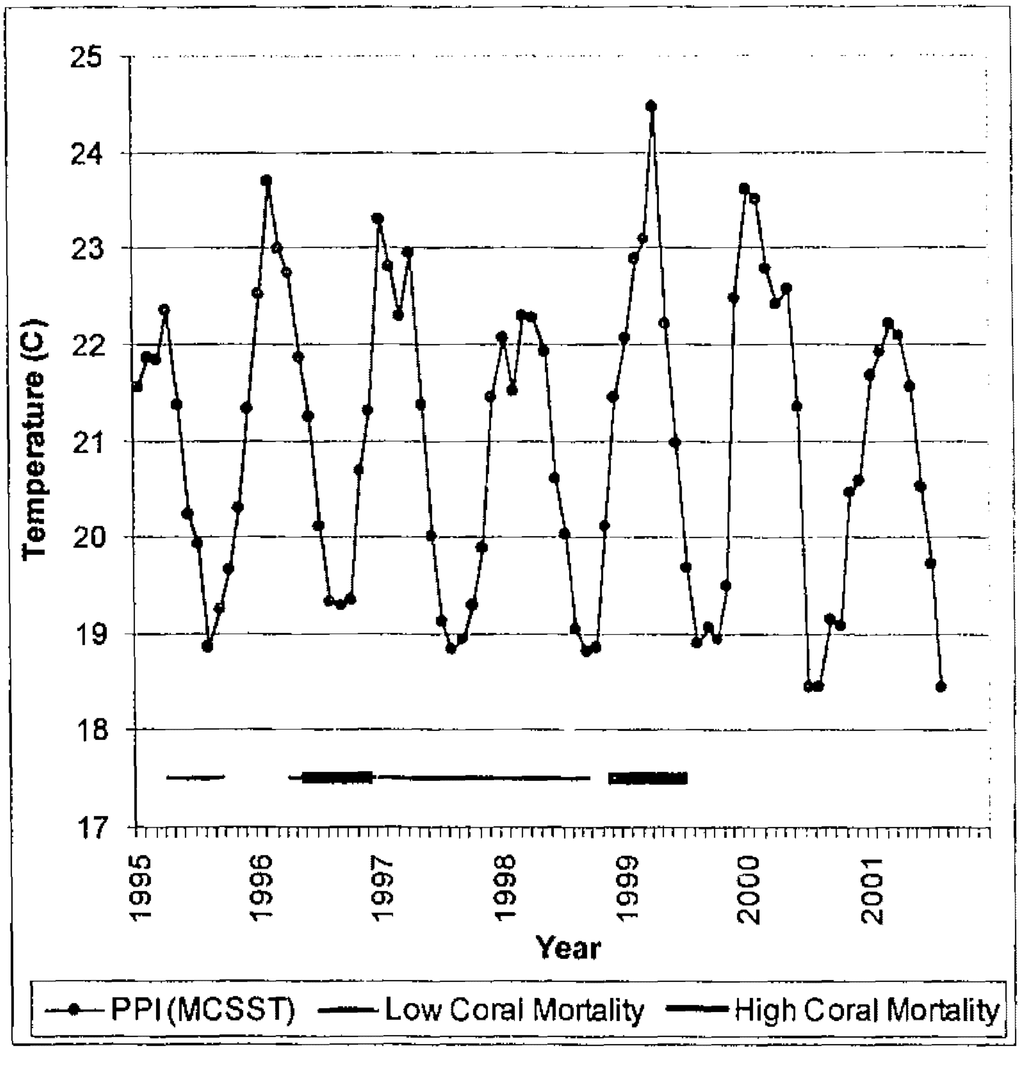

Figure 3.6 - Monthly mean SST (NOAA/AVHRR) and coral bleaching incidences at Parker Point (PPI), Rottnest Island between 1995-2001, as observed by Dr. B. Hutchins.

CHAPTER 4.0
DISCUSSION

4.1 Evaluation of satellite data to determine SSTs

Studies conducted by Pearce *et al.*, (1989) within the offshore waters of WA, examined seven algorithms available at the time for SST extraction. The best results were obtained by the McMillin & Crosby algorithm, which yielded a bias of -0.14°C and an RMS of 0.55°C (Pearce *et al.*, 1989). Until mid 1995, satellite-derived SST data relied on the McMillin & Crosby algorithm, but was subsequently superceded by the MCSST algorithm, which takes into account the scan-angle across the swath ('edge effect') (A. Pearce, pers. comm.).

While MCSST was not examined in the study by Pearce et al. (1989), the present study has shown that, when compared with *in situ* data approximately 1km from the coast, the MCSST algorithm yielded a lower bias of 0.086°C and an RMS of 0.46°C, compared with a bias of -0.46 °C and an RMS of 0.72 °C for McMillin & Crosby. The latter algorithm was also shown to provide slightly higher and more variable temperature values than MCSST.

The satellite-derived data using the MCSST algorithm corresponded closely with both the nearshore and offshore *in situ* data. Although there was little difference between nearshore and offshore comparisons, more outliers were witnessed when comparing satellite data with nearshore logger-derived data. Such a result indicates that proximity to coast may affect the accuracy of the satellite readings. This is explained by the fact that the size of the satellite resolution (or pixel size) is 1km^2, and even with manual selection of pixels to avoid land contamination, such contamination may occur due to exposure of the reef or the inability to define small areas of land during the selection process. The resulting partial reflection of land surface temperatures due to land-contamination, is likely to provide very much warmer temperatures in summer, or cooler temperatures in winter than sea surface temperatures. Satellite SST data in Geordie Bay (GB) would be particularly susceptible to land contamination, as the site is contained within a small bay, with surrounding rocky outcrops (Figure 2.1) within 1km of the coast. This effectively means that small bays and areas littered with rocky outcrops (or exposed reef) are difficult to measure using satellite technology. This may result, however, in the next-nearest-to-shore SST pixel being selected, as pixels any closer to the coast will most often be land contaminated. For this reason satellite data is found to better match with the offshore logger data, which are shown to be representative of more nearshore SSTs.

4.2 Limitations of satellite and in situ data

Because the NOAA/ AVHRR satellite orbits vary in time, with each orbit over Rottnest Island occurring at a slightly different time from the preceding day (time-drift), it has been necessary to match the time of orbit with SSTs measured by the loggers at the same time. Since nearshore logger temperatures over the winter/spring period displayed a clear diel pattern, with SSTs cooling down after approximately 1400hrs and warming up again around 0600hrs, a two-hour difference in orbital time could result in a small change in temperature. Examining Figure 3.5, it is indicated that this change in temperature with time will be, at maximum, 0.2°C per hour, during the winter months. It is anticipated that this difference would be greater in summer. This means that simply comparing satellite and logger data could result in temperature discrepancies, if the specific logger time is not extracted to match with the time of the satellite orbit. In addition to this, if satellite-extracted SSTs are simply plotted over a period of time, a general increase in temperatures may be witnessed. This temperature increase may thus not be reflective of actual SST trends, but is rather resultant of the fact that time-drift has occurred, and the satellite may be passing at a warmer period of the day, especially in summer. The opposite scenario, when a decreased temperature trend is witnessed, may also occur, with the satellite passing during cooler periods of the day, from preceding orbits.

When utilising *in situ* data, the risk of logger vandalism is prevalent. Of the eight loggers deployed during the period of this study, three were either vandalised or lost. Temperature loggers and software are reasonably expensive, and this should be considered if cost-restrictions exist, as satellite data are often free of charge. It was also found that the deployment of these loggers was often perilous, with large swells, high-energy beaches, storm events, and sharp reef contributing to the dangerous conditions. In order to allow for the best match with the time of the satellite orbit, loggers were set up to record SSTs every 15minutes. In addition, failure of loggers to record SSTs was also experienced, an incident which would not be experienced with satellite-data extraction.

4.3 Climatology of nearshore waters at Rottnest Island

The satellite-derived data have been utilised to examine spatial and temporal trends in SST at Rottnest Island. Thomson's Bay displayed the greatest temperature variance, however, this difference was seen to be less than only 0.4°C from the other sites. However, using logger-derived data, the temperature between Thomson's Bay and the other nearshore sites varied at most by 0.1°C, suggesting that logger derived data have a better resolution than the remotely sensed SSTs. As stated earlier, the resolution of satellite data will generally fall within ± 0.75°C. Compared with the other sites, SSTs at Thomson's Bay tended to be higher in the summer and lower in the winter. Parker Point and Geordie Bay were seen to correspond closely (Figure 2.1). Temperature differences between sites are likely to be largely due to bathymetry. Thomson's Bay was the shallowest of the sites, while Geordie Bay and Parker Point exhibited similar bathymetry (Figure 2.1). In summer, there is a net heat flux from the sun and atmosphere into the ocean, so shallower waters heat up more than deeper offshore waters, while heat loss to the atmosphere in winter results in appreciable cooling of the coastal waters (Cresswell & Golding, 1980; Gentilli, 1972). It is likely that these factors have resulted in the temperature differences between the sites.

Not surprisingly a distinctly annual trend is apparent in the nearshore waters of Rottnest Island, with warmer summers and cooler winters. The maximum summer time temperature was 24°C, while the minimum wintertime temperature was 18.5°C. This means that generally, temperatures over the year at Rottnest Island only differ annually by approximately 5.5°C.

A relatively large degree of inter-annual variability in the SSTs at Rottnest Island was observed. The summer of 1998 - 1999 displayed temperatures elevated above any of the other six years examined in the study. It was found that two years of warmer SSTs were generally followed by one year of decreased SSTs; however, the short data record utilised restricts further comparisons of this possible trend. This trend does, however, seem to be related to La Niña and ENSO phenomenon, with the warmest annual SSTs occurring during 1996, 1999, and 2000, the same years that La Niña conditions were prevalent (Pearce, pers. comm.). It can therefore be assumed that when La Niña conditions are present, the mean annual SSTs will generally be higher than those experienced in non- La Niña years. This is due to the Leeuwin Current being influenced by La Niña conditions, with stronger currents extending further down the coastline during these times (Pearce, *et al.*, 2001).

The results show that, although a typical southern hemisphere Mediterranean summer lasts from December to February (Playford, 1988), warm SSTs are still apparent in April at Rottnest Island. Such a trend is highlighted by comparisons between SSTs in the nearshore waters off the mainland of Western Australia (Marmion), with mean temperatures within the nearshore environment at Rottnest Island. Distinctly cooler temperatures are observed at Marmion than at Rottnest Island (Figure 4.1) (Pearce *et al.*, 1999). This is advocated to be due to the presence of the Leeuwin Current (Pearce, *et al.*, 2001), which usually travels down from the north, reaching Rottnest Island by March. The Leeuwin Current is usually present until August, when it again recedes (Pearce, *et al.*, 2001).

This trend highlights the fact that the Leeuwin Current does not usually extend into the shoreward region of the Western Australian mainland, but does flow around Rottnest Island (Figure 1.1a). The presence of tropical coral at Rottnest Island has previously been suggested to be due to the fact that, on occasions, the Leeuwin current 'curls' around to reach Parker Point (Hutchins, pers. comm.). However, SSTs examined in this study, suggest that the effect of the Leeuwin Current is not restricted to this region, since no marked difference occurred in SSTs between the three sites.

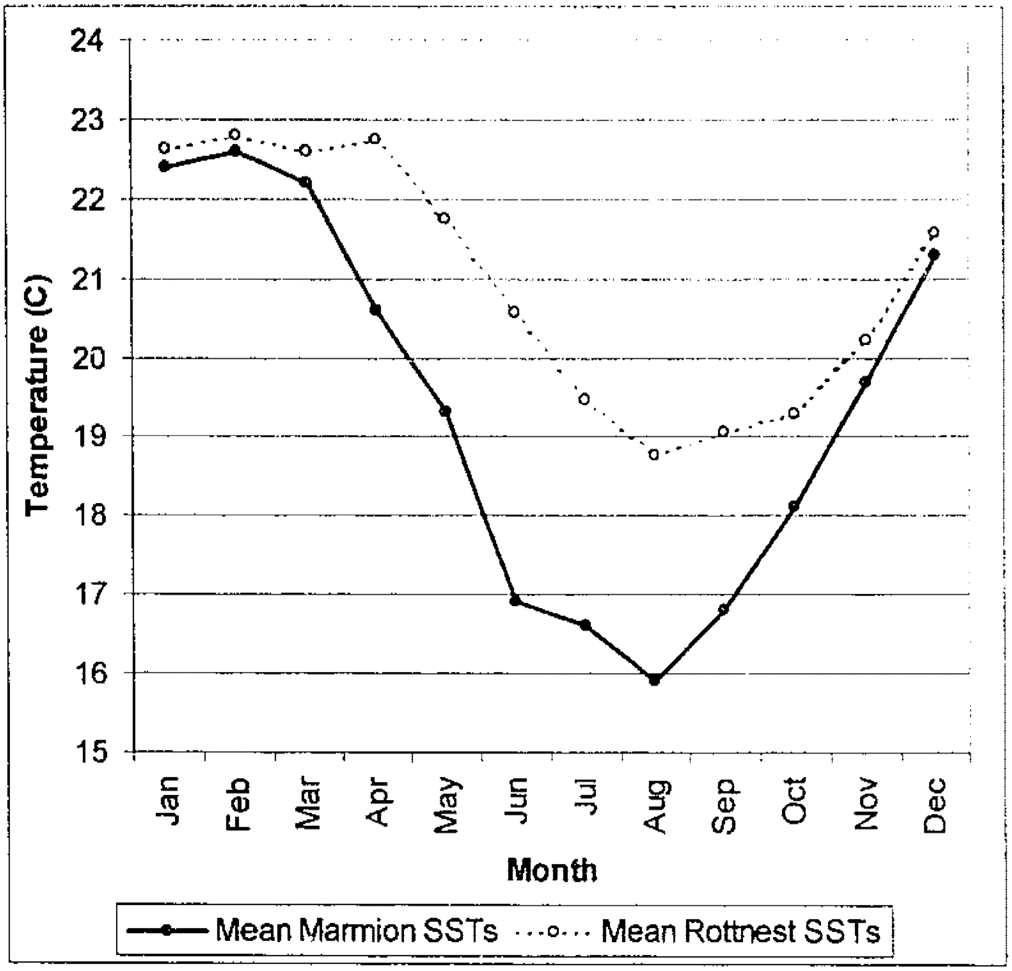

Figure 4.1 – Nearshore mean monthly SSTs at Marmion 1990-1994 (Pearce, *et al.*, 1999). Compared with Figure 3.8, a much cooler mean monthly SST pattern is witnessed.

4.4 Is coral bleaching at Rottnest Island related to temperature?

Coral bleaching at Rottnest Island is poorly documented, and this study has utilised coral bleaching observations by Dr. Barry Hutchins of the Museum of Western Australia. The coral bleaching incidences are based upon his field notes of observed coral mortality for the period 1995-2001. It should be noted that additional events may have occurred, and also duration, start, and recovery periods are open to question. However, Dr. Hutchins' observations will be utilised in an attempt to associate the observed coral bleaching events with elevated SSTs.

At one stage it was thought that elevated SSTs, forming degree-heating weeks (DHWs), might have been responsible for the coral mortality witnessed at Rottnest Island, between 1995-2001 (Dr. B. Hutchins, pers. comm.). The temperature range for hermatypic tropical corals, which are found at Parker Point, Rottnest Island, are between 18-28 °C. Temperatures elevated by 1°C above the upper threshold for one week or more were considered to be responsible for coral bleaching (IUCN, 2000). However, temperatures never exceeded this upper threshold level at Rottnest Island.

As Rottnest Island is the southern-most limit for the growth of tropical corals (Ward, 1994), it could be considered that the corals at this island may have in fact acclimatised to the cooler environment. Due to the possibility of acclimatisation, it seems reasonable to apply a specific DHW for Parker Point, which has been averages based on the mean maximum summer time temperatures for the period 1995-2001 (22.7°C). Furthermore, due to the fact that cooler water temperatures may limit the survival of corals (Ward, 1994), this study has derived a new parameter, a degree-cooling week (DCW), where temperatures fall below the mean minimum wintertime temperature (18.5°C) by 1°C for over one week.

The elevation of temperatures to the site-specific DHW indeed occurred four times during the seven-year period (Table 3.1). Of these events, two occurred in 1999. Coral bleaching was already present prior to one of these DHWs in April-May 1999, thereby suggesting that factors other than elevated temperatures induced coral mortality. The DHW during late February to early March 1999, occurred when coral mortality was observed at Parker Point. However, the remaining two DHWs occurred at times when no coral bleaching events were observed. This indicates that coral bleaching at Rottnest Island, based on available data, is unlikely to be caused by elevated SSTs. Neither do waters cool to below desirable temperatures, which would be unfavourable coral colonisation and growth. As bleaching has been witnessed throughout varying seasons, at both low and elevated temperatures, and varying duration (Hutchins, pers. comm.), it can be suggested that the coral mortality at Rottnest Island is not thermally induced, however, further studies to accurately document and quantify coral mortality, at Parker Point, are imperative.

While the above suggests that coral mortality is not specifically temperature induced, temperature may still play a role indirectly. Temperature may affect other variables that impact upon the coral. It has been postulated that the coral mortality at Rottnest Island, may partly be influenced by starfish predation. These predators feed at night and it is deliberated that their nocturnal behaviour has lead to their exclusion as a candidate for the cause of coral bleaching, as they are rarely sighted by researchers (Hutchins, pers. comm.). However, due to study restrictions, this conjecture could not be further analysed. Other factors, which may influence the survival of coral communities at Rottnest Island, include natural phenomena such as algal smothering, storm events, and reef exposure, or human-induced disturbance such as pollution, anchorage and mooring damage, snorkellers and SCUBA divers, and effluent discharge (SCUBA, 1998).

CHAPTER 5.0
MANAGEMENT IMPLICATIONS & CONCLUSIONS

5.1 Management Implications

The knowledge of spatial and temporal temperature variance is fundamental for the management of marine ecosystems, such as coral reefs, which are thermally sensitive marine organisms (IUCN, 2000). Knowledge of whether offshore temperatures are indicative of nearshore SSTs, will also allow for the improved management of nearshore marine ecosystems.

The principal aim of this research project has highlighted the value and expediency of remotely sensed data for use in environmental management, with particular applications in marine ecosystems and fisheries administration. Many marine species are highly sensitive to changes in water temperature, and will often expire at elevated temperatures (IUCN, 2000). This temperature sensitivity of marine species is becoming of serious concern, with global warming alerting environmental managers of the crisis they could face with foreseen impacts on commercial fisheries, tourism and marine biodiversity. Tropical corals in particular are highly sensitive to thermal increase above mean maximum temperatures. Satellite remote sensing of sea surface temperatures in nearshore environments, where these marine organisms often reside (particularly on the Western Australian coast), will allow for the monitoring and management of thermally-related phenomena.

As an example of the use of satellite-derived data for the management of nearshore environments, the present study has shown, that coral bleaching at Parker Point, Rottnest Island, for the period 1995-2001, was in fact unlikely to have been thermally induced, and other natural and human induced causes should be considered.

Where *in situ* measurements are not available or impractical, satellite remote sensing is a viable option for determining SSTs approximately 1km from the coast. Ultimately, *in situ* readings are more reliable than remotely sensed data, as several types of problems may occur in analysing observations of SST provided by satellite technology. For example, land contamination will lead to inaccurate results, as will sun-glint , atmospheric disturbances, and cloud-cover. Both this study, and that of Gohin & Langlois (1993), have shown remotely sensed images may provide a somewhat biased SST contaminated by the atmosphere. In obtaining historical data preceding 1995, the McMillin & Crosby SST algorithm for the NOAA/AVHRR satellite must be utilised. However, this algorithm was found to be less accurate than the MCSST algorithm, which was introduced in May 1995, and should be taken into account for future studies.

]Nearshore satellite SST extraction requires intricate manual processing techniques in order to distinguish the closest satellite pixel to the coast. It is often found that the closest pixel to the coast contains both land and water, and thus the next-closest pixel must be selected. This often results in the pixel chosen actually being approximately 1km offshore (size of one satellite pixel), and with technology at present, this cannot be avoided. Comparisons between offshore and nearshore *in situ* data has shown that offshore SST data are highly representative of nearshore SSTs. Hence, nearshore satellite SST extraction is possible for regions approximately 1km from the coast, which is representative of SSTs within 1km of the shore.

Limitations associated with the acquisition of remotely sensed data include the time taken to manually extract desired pixels from the data obtained. This is an involved and time-consuming process, however it is quite obviously more time efficient in extracting historical SSTs, when compared to waiting for example one entire year to extract and annual data set derived from *in situ* means. Using remotely sensed data is often also less favourable than *in situ* derived data if a high degree of spatial resolution is required. Depending also on your location, satellite data may be expensive to obtain, although this study found that temperature loggers were also and expensive option, with loss and vandalism adding to the expense.

5.2 Summary

Many key findings were made regarding the methods required for nearshore sea surface temperature data extraction (summarised in Figure 2.8), which has previously not been attempted. Coupled with this, salient findings regarding the use of remote sensing in extracting SSTs, and applying these data to determine climatology and to relate these findings to environmental phenomena were also made. These findings are summarised below:

1. The MCSST satellite SST algorithm is more accurate in representing SSTs, with a lower bias and root mean square (difference), and higher degree of correlation than the McMillin and Crosby algorithm. MCSST satellite data correspond within ± 0.5°C to *in situ* data (approximately 1km from the coast), 60% of the time, and 90% of the time within ± 0.75°C;
2. Where temperature loggers are not available, satellite SSTs derived approximately 1km offshore, are shown to be highly representative of SSTs

within the first kilometre of the shore, and thus satellite remote sensing is a viable option for determining SSTs in nearshore environments;

3. Limitations of satellite data include land contamination, cloud-cover and sun-glint;
4. Limitations of temperature loggers include hazards involved with deployment/retrieval, and vandalism;
5. Satellite SST extraction and examination allows for historical data set construction and climatological establishment;
6. Remotely sensed nearshore SSTs for Rottnest Island between 1995-2001, show that coral bleaching, at Parker Point, is unlikely to be solely attributed to elevated temperatures.

CHAPTER 6.0
REFERENCES

Bernstein, R. L. (1982). "Sea surface temperature estimation using the NOAA-9 satellite Advanced Very High Resolution Radiometer". IN: Journal of Geophysical Research Vol. 87, pp. 9455-9465.

Chiswell, S. & Stanton, B. (1992). Comparison of AVHRR measurements of sea surface temperature with surface observations around New Zealand. New Zealand Journal of Marine and Freshwater Research, 1992, Vol. 26, pp. 303-309.

Cresswell, G. R. & Golding, T.J. (1980). Observations of a south flowing current in the southeastern Indian Ocean. IN: Deep Sea Research, 27A, pp.449-466

Easton, B.W. (1995). Rottnest Island Review - September 1995. Rottnest Island Authority, Fremantle.

Fox, M.F., Kester, D. R., Andrews, J. E., Magnuson, A., & Zoski, C. G. (2000). Seasonal Warming Of Narrangsett Bay And Rhode Island Sound 1997: Advanced Very High Resolution Radiometer Sea Surface Temperature And In Situ Measurements. IN: Journal Of Geophysical Research, Vol. 105, No. C9, Pp. 22,071-22,082, September 15, 2000.

Garrabou, J., Perez, T., Sartoretto, S., Harmelin, J.G. (2001). Mass mortality event in red coral *Corrallium rubrum* populations in the Provence region (France, NW Mediterranean). *In*: Marine Ecology Progress Serial, Vol. 217:263-272, July 31, 2001.

Gentilli, J. (1972). "Ocean-Atmosphere Relations On The Western Australian Coast." **IN:** Proposal For Marine Environmental Studies Off The Western Coast Of Australia, CSIRO, Pp 17-37.

Gosliner, T. M., Behrens, D. W. & Williams, G. C. (1996). Coral Reef Animals of the Indo-Pacific. Sea Challengers, California.

Hassell, C.W. & Kneebone, E.W.S. (1960). The Geology of Rottnest Island. University of Western Australia, Department of Geology, B. SC. Honours thesis (unpublished).

Hodgkin, E.P. & Di Lollo, V. (1958). The Tides of Southwestern Australia. Royal Society of Western Australia v.41, p.42-54.

Hopkin, S. (2001). The Flushing Characteristics of Rottnest Bays. Paper in preparation.

Hutchins, J.B. (1994). Recruitment of Tropical Reef Fishes in the Houtman Abrolhos Islands, Western Australia. Western Australian Museum, Perth,

Hutchins, J.B. (1998). A Snorkellers' Guide to Rottnest Island. Rottnest Island Authority, Fremantle.

Hutchins, J.B. (1999). Mortality of *Pocillopora* coral at Rottnest Island, Western Australia. IN: Walker, D.I. & Wells, F.E. (Eds.) (1999). The Seagrass Flora and Fauna of Rottnest Island, Western Australia. Western Australian Museum, Perth.

Hutchins, J.B., & Pearce, A.F. (1994). Influence of the Leeuwin Current on Recruitment of Tropical Reef Fishes at Rottnest Island, Western Australia. **IN:** Bulletin of Marine Science, Vol 54, pp. 245-255.

Imberger, J. (2000). Rottnest Island Environmental Management Plan. Unpublished Thesis, The University of Western Australia.

IUCN (2000). Reefs at Risk - Coral reefs, human use and global climate change - A program of action. IUCN, Switzerland.

Jarvis, N. (1986). Western Australia, an atlas of human endeavour. Western Australian Department of Lands and Surveys, Perth.

Juppenlatz, M. & Tian, X. (1996). Geographic Information Systems and Remote Sensing. McGraw-Hill Book Company, New South Wales.

Llewellyn-Jones, D. T., Minnett, P. J., Saunders, R. W. & Zavody, A. M. (1984). Satellite multi-channel infrared measurements of sea surface temperature of the N.E. Atlantic Ocean using AVHRR/2. Meteorological Society, 1984, Vol. 110, pp. 613-631.

Myers, D. (1987). Satellite Sensing Australia. Western Australian Satellite Technology and Applications Consortium, Perth.

NESDIS Coral Reef Bleaching (2001). [on-line]. Available http://orbit-net.nesdis.noaa.gov/orad/coral_bleaching_index.html.13/03/01

Pearce, A. F. & Cresswell, G. (1985). Ocean Circulation off Western Australia and the Leeuwin Current. Sheet No. 16-3. July 1985. CSIRO Marine Laboratories, Western Australia.

Pearce, A.F., Cresswell, G. & Griffin, D. (2001). The Leeuwin Current - life of the West. CSIRO Marine Research, Fact Sheet No. 44, August 2001.

Pearce, A. F., Rossbach, M., Tait, M., Brown, R. (1999). Sea temperature variability off Western Australia 1990 to 1994. Fisheries Research Report No. 111, 1999, Fisheries Western Australia.

Pearce, A. F. & Scott, A. (n.d.). The Climate of Rottnest Island. The Rottnest Island Board, Perth, WA.

Pearce, A. F., Prata, A.J., & Manning, C.R. (1989). "Comparison of NOAA/AVHRR-2 sea surface temperatures with surface measurements in coastal waters. Taylor & Francis, Perth.

Pearce, A.F. & Pattiaratchi, C. (1997). "Applications of satellite remote sensing to the marine environment in Western Australia". Royal Society of Western Australia, Perth.

Pattiaratchi, C.B. (1992). Coastal environmental mapping using Landsat data. Proceedings pf the Central Symposium of the International Space Year Conference, 739-743. The Committee, Munich.

Playford, P.E. (1983). Geological Research on Rottnest Island. Royal Society of Western Australia. V.66, p.10-15.

Playford, P.E. (1988). Guidebook to the Geology of Rottnest Island. Geological Society of Australia, WA Division and the Geological Survey of Western Australia, Perth.

SCUBA II (1998). Pocillopera Reef - Rottnest Island - Marine Monitoring 1992 - 1998. Rottnest Island Authority, Fremantle.

Stramma, L., Cornillon, P., Weller, R. A., Price, J. F., Briscoe, M. G. (1986). Large Diurnal Sea Surface Temperature Variability: Satellite and In Situ Measurements. **IN:** American Meteorological Society, Vol. 16. pp. 827-pp839

Strong, A.E., Barrientos, C.S., Duda, C., & Sapper, J. (1996). Improved Satellite Techniques for Monitoring Coral Reef Bleaching. International Coral Reef Society, Panama.

Veron, J.E.N. and Marsh L.M. (1988). Hermatypic corals of Western Australia and annotated species list. Records of the Western Australian Museum Supplement 29: 1-136.

Ward, S. (1994). The effect of damage on the growth, reproduction and storage of lipids in the scleractinian coral Pocillopera damicornis (Linnaeus).

IN: Journal of Experimental Marine Biology and Ecology Vol. 187, pp. 193-206.

WCED, (1990). Our Common Future - Commission for the Future - Australian Edition. Oxford University Press, Melbourne.

Wellington, G. M., Glynn, P. W., Strong, A. E., Navarrete, S. A., Wieters, E. & Hubbard, D. (2001). Crisis on Coral Reefs Linked to Climate Change. EOS, Vol.82 No1, 2/01/2001.

Yokoyama, R. & Tanba, S. (1991). Estimation of sea surface temperature via AVHRR of NOAA-9 - comparison with fixed buoy data. **IN:** International Journal of Remote Sensing, 1991, Vol. 12, No. 12, pp. 2513-2528.

APPENDIX 1.0

Rottnest Island Back-ground

Climate of Rottnest Island

According to a study by Pearce & Scott (n.d.), the weather conditions experienced at Rottnest Island are very similar to those experienced on the Perth mainland. Maximum summer land-temperatures are usually higher in Perth than Rottnest Island, but in winter there is little difference. The higher summer temperatures on the mainland are most likely due to anthropogenic influences such as vehicle exhausts creating a micro-climate, and reduced natural vegetation, and also oceanographical influences such as reduced sea-breeze intensity, and distance from the sea. These differences highlight the influences of the surrounding ocean on the temperatures experienced at Rottnest Island (Figure 4.1). The ocean provides a cooling influence in the summer and a warming influence in the winter, and is supplemented by a warm current from the tropics in winter (refer to section 1.4.1). The Leeuwin Current is often responsible for some of the oceanic temperature influences experienced at Rottnest Island. These influences may vacillate between bays around the island, and individual-bay temperature studies are required to attain site specific SST's.

Rainfall

Most of Rottnest's rainfall occurs between May and September, as with the mainland, however the Rottnest percentiles are slightly lower on average than Perth (Figure 7.1). Pearce & Scott (n.d.) speculate that the main reason for this rainfall difference is that the land area of Rottnest is too small to influence significantly the vertical motion of the air, which is necessary to produce rain. High rainfall velocities may result in physico-chemical changes in the sea-water, such as salinity shifts. It is postulated the rainfall may directly influence marine biota, and has been presupposed to be one of the contributing factors to the coral bleaching phenomenon.

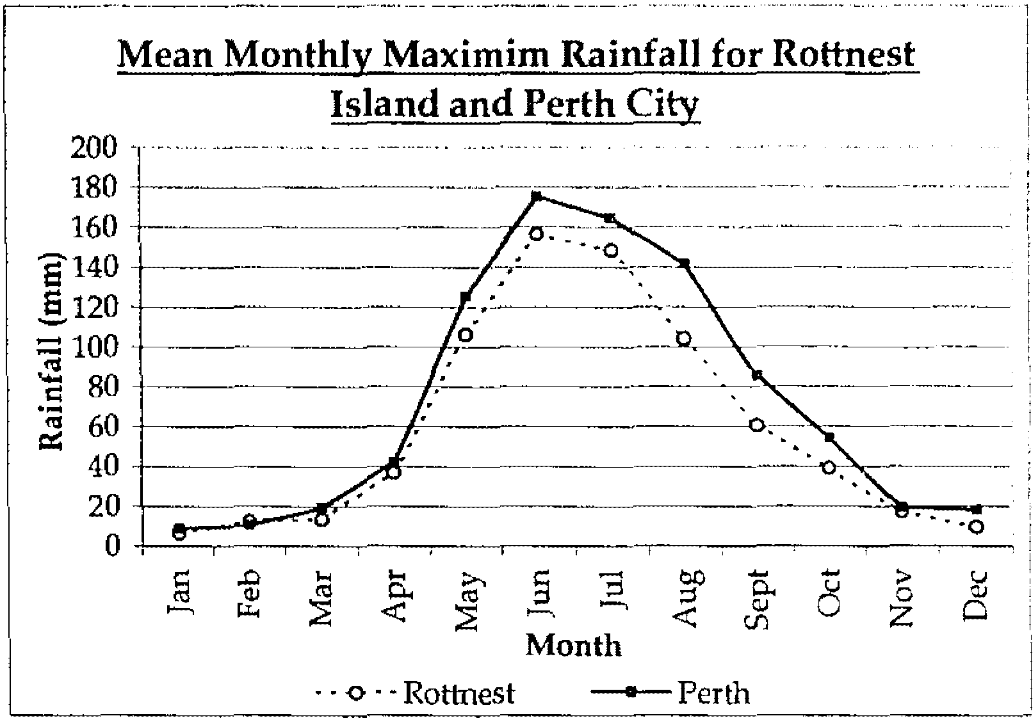

Figure 7.1 Mean annual rainfall for Rottnest Island and the Perth mainland (Courtesy of Bureau of Meteorology, 2001).

Winds

Winds in the Southern Hemisphere blow in an anti-clockwise direction around a high-pressure system. For this reason winds overnight and in the mornings are frequently southeast or easterly (Pearce *et al*. 1999). In summer, when air passes over land, it becomes warmed by the earth's surface, and the increasing air temperature is directly proportional to the amount of land it passes over. The greater distance of land the air passes over, so the more warmed it becomes. As the air temperature rises so the density of the air decreases and the atmospheric pressure falls (Pearce *et. al*, 1999). This causes the development of a low-pressure trough, which develops northeasterly or northerly winds and temperatures on the mainland rise. The low-pressure trough eventually splits the high-pressure ridge and moves eastwards. As a new high moves eastwards over the state, cooler air from the south moderates temperatures for a few days until the sequence is repeated.

During the summer months (December to February) Rottnest Island and the mainland experience the equable effects of the sea breeze traveling in a southwest to southerly direction. This wind results from the temperature difference between the hot land and the cool sea during the hottest part of the day (Pearce *et. al*, 1999), but can however be prevented from occurring on some days dues to the strength of offshore winds. Summer is also the season when tropical cyclones form along the northern areas of the Western Australian coastline, and typically eight to twelve such cyclones occur in any one summer.

Through autumn and into winter the high-pressure ridge moves northwards, allowing low-pressure systems to affect southwestern Australia. These 'lows' travel in a clock-wise direction and their associated cold fronts move eastwards to produce rain, showers and occasionally strong to gale force winds. Between these wet and sometimes windy periods, the days are often partly sunny with light winds (Pearce *et. al*, 1999).

Bio-erosion and Other Factors Affecting Rottnest Corals.

Observations, by Hodgkin (1970) and Black & Johnson (1983), on the major role of molluscs (at Rottnest Island) in eroding the notches and platforms of the tropical reef systems, have been made. Limpets, other gastropods, and chitons actively abrade the limestone reef with their teeth while scraping away the algae on which they feed. Some of the algae are endolithic (their filaments extend into the limestone) and several species of molluscs evidently scrape away the surface of the limestone in order to feed on these filaments, resulting in the bioerosion of the reef system (Black & Johnson, 1983). Other organisms that contribute to this bioerosion include sea urchins, boring bivalves, and boring clionid sponges. Bioerosion may also be caused by natural disturbances such as mechanical damage caused by extreme storm events. Superlative wave and wind action may lacerate the corals from the reef system, and thus cause mass coral mortality. Physico-chemical influences such as nutrient content of the water, salinity, turbidity and temperature are constitutive to the survival of the corals, and must be monitored and managed appropriately.

El Niño, La Niña, the Leeuwin Current and the Capes Current.

Phenomena such as El Niño (where prolonged "downwelling" of warmer waters displaces the cooler waters of the ocean currents) and La Niña (where the "upwelling" of cooler water, displaces the normally warmer SST's), in Western Australia are linked with the Leeuwin Current. The Leeuwin Current, a body of warm nutrient-poor tropical water, extends from Indonesia southwards, along the Western Australian coast, arriving in early autumn, and its duration until the end of winter. Both phenomena can be equally devastating, as a simple one-degree change in maximal or minimal tolerance levels, has the capacity to bleach and destroy an entire coral community. Coral reefs support a variety of sea-life and provide resources of significant economic importance such as fishing and recreation. Coral bleaching, induced by high water temperatures, has raised concerns about these fragile ecosystems.

Tides

The maximum daily tidal range at Rottnest Island (Figure 3.1) is approximately 1m, and the extreme range is 1.5m (Playford, 1988). Hodgkin and Di Lollo (1958) state that the sea level along the Rottnest coast is particularly strongly influenced by air pressure, water temperature, and prevailing winds.

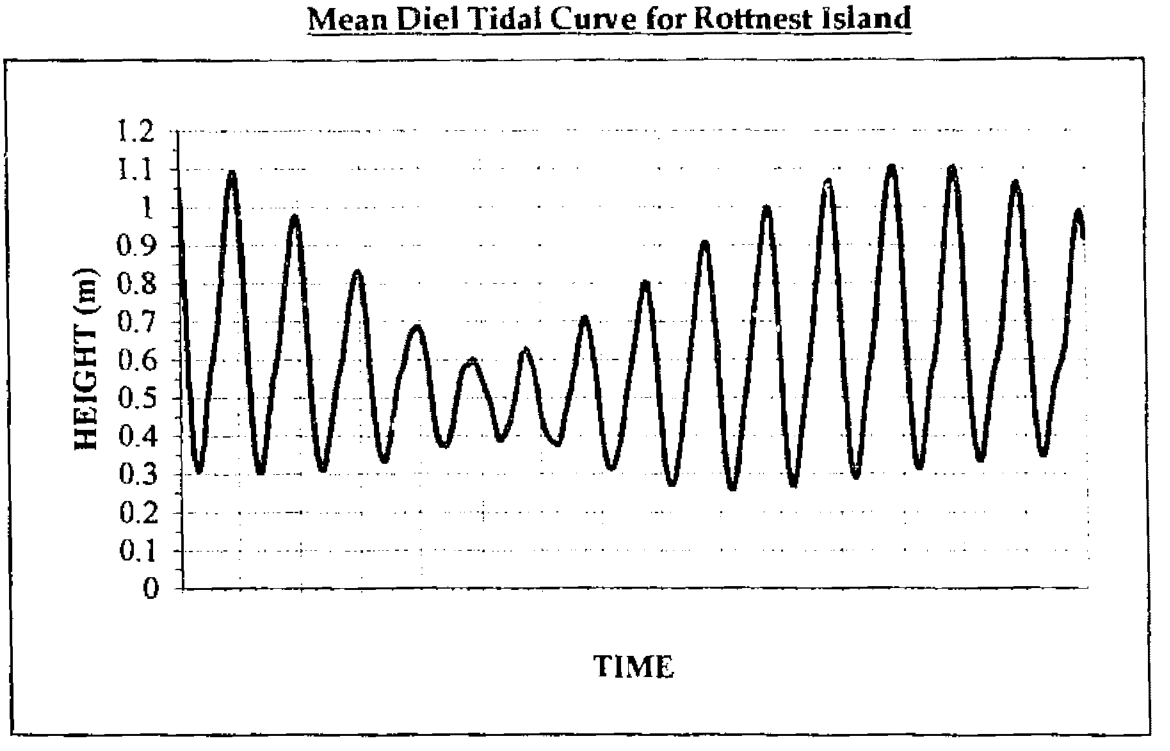

Figure 7.2 Diel (day and night) tidal curve for Rottnest Island (Courtesy of Tony Lamberto and the Bureau of Meteorology).

Continental Shelf Waves

Tropical cyclones generated along the northwest continental shelf off Western Australia have the capability to alter the prevailing current system at Rottnest Island. These cyclones can produce wind gusts up to $40ms^{-1}$ and generate continental shelf waves (Imberger, 2000). These waves (often reaching 12 ft) are often responsible for mechanical damage to the reef ecosystems, and may result in coral mortality.

Sea Level Changes

There is evidence displayed at Rottnest Island of Quaternary sea-level changes (Teichert, 1950; Fairbridge, 1958; Hassel & Kneebone 1960; Playford 1983). This evidence is seen as elevated marine deposits, elevated shoreline platforms and notches (Playford, 1988). Elevated fossilised coral reefs exist at the island, suggesting that sea-level changes may threaten the subsistence of the corals. The reef systems of Rottnest Island were built mainly by *Acropora*, which does not form living reefs today further south than the Houtman Abrolhos, 350km north (Playford, 1988). The fact that *Acropora* once inhabited the waters of Rottnest indicates warmer water conditions in this area during the last interglacial period (Playford, 1988). This indication suggests that the corals of Rottnest Island have been subjected to varying global and localised climatic conditions, which directly affect their survivorship. Hence any future changes in sea level or mean sea surface temperature may affect the vitality of Rottnest tropical corals.

Over the past 100 years sea level has risen by 10-12cm. Increasing levels of greenhouse gases in the atmosphere are expected to result in a global temperature rise of about 0.2°C per decade for the next 100 years (Imberger, 2000). Consequently, thermal expansion of the ocean and an influx of freshwater from melting glaciers and ice, should result in a global sea level rise. The rate, magnitude and direction of sea level change will vary locally (and regionally) in response to coastline features, changes in ocean currents, differences in tidal patterns and seawater density and vertical movements of the land itself as it adjusts to the increased load. For this reason it is important to monitor site-specific environments in order to attain an understanding of the temperature influences experienced provincially (please refer to 'Results' for temperatures experienced within three selected bays, nearshore and offshore Rottnest Island).

Oceanic Currents

Rottnest Island is influenced primarily by both the Leeuwin Current and the Capes Current (Figures 1.0 a and b). The Leeuwin Current is driven by an along-shore steric height gradient which seasonally interchanges the cool, high salinity sub-tropical waters of the southern areas of the west coast, with warmer, less saline tropical waters, from Indonesia (Pearce & Cresswell, 1985). During summer, Rottnest Island and surrounding waters, generally experience a relatively weak Leeuwin Current and strong Capes Current, due to the fact that southerly winds dominate. A seasonal shift occurs in winter where the southerly winds are largely absent and hence the Leeuwin Current dominates (Imberger, 2000).

The Capes Current originates between Cape Leeuwin and Cape Naturaliste and is driven by persistent southerly winds in the region. The Capes Current transports cold water from the Southern Sea, northwards along the WA coast. It runs closer to the coast than the Leeuwin current, and so affects the eastern auxiliary of Rottnest more greatly than the outer western side (Figure 1.0a) (Imberger, 2000).

Table 7.1 Seasonal Climatic Summary for Rottnest Island

PARAMETER	SUMMER	AUTUMN	WINTER	SPRING
Mean Temperature (°C)	24.7	22.8	17.5	22.2
Mean Rainfall (mm)	9.6	52.3	136.3	39.0
Wind Direction a.m.	From West	From West	From SW	From West
Wind Direction p.m.	From NE	From NE	From East	From N E
Wind Speed (km/hr) a.m.	25.3	25	27.27	24.7
Wind Speed (km/hr) p.m.	28.9	23.7	25.5	26.0
Clear Days	14.8	9.3	5.7	9.0

NE - North East SW - South West [Source: Bureau of Metrology, 2001]

APPENDIX 2.0

Satellite Orbital and Logger Information

Table 7.2 NOAA Satellite orbital Details

Year	Satellite	Beginning Orbit	End Orbit
1995	NOAA 9 NOAA 14	N0951886 N1401507	N0953496 N1405161
1996	NOAA 14	N1405189	N1410310
1997	NOAA 14	N1410338	N1415474
1998	NOAA 14	N1415488	N1420611
1999	NOAA 14	N1420639	N1425776
2000	NOAA 14	N1425790	N1430943
2001	NOAA 14	N1430957	N1433245

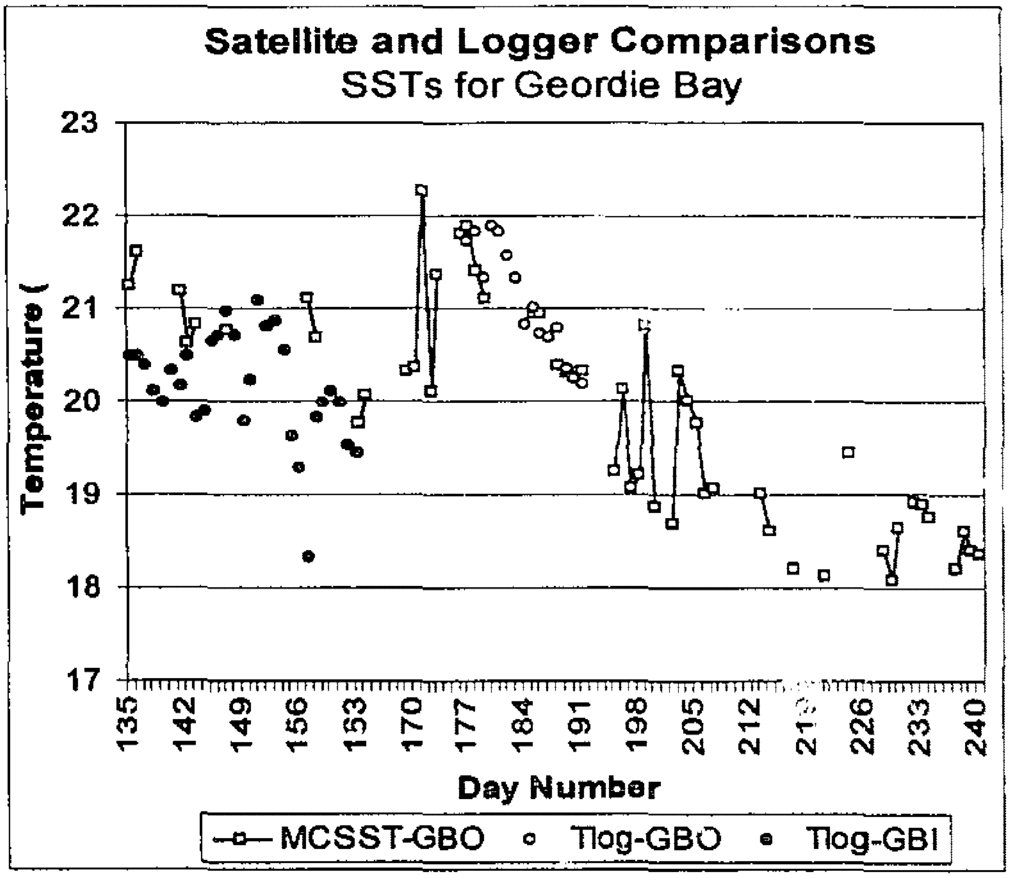

Figure 7.3(a) - Satellite derived data, utilising MCSST, and logger derived data for the period May-September 2001, at Geordie Bay.

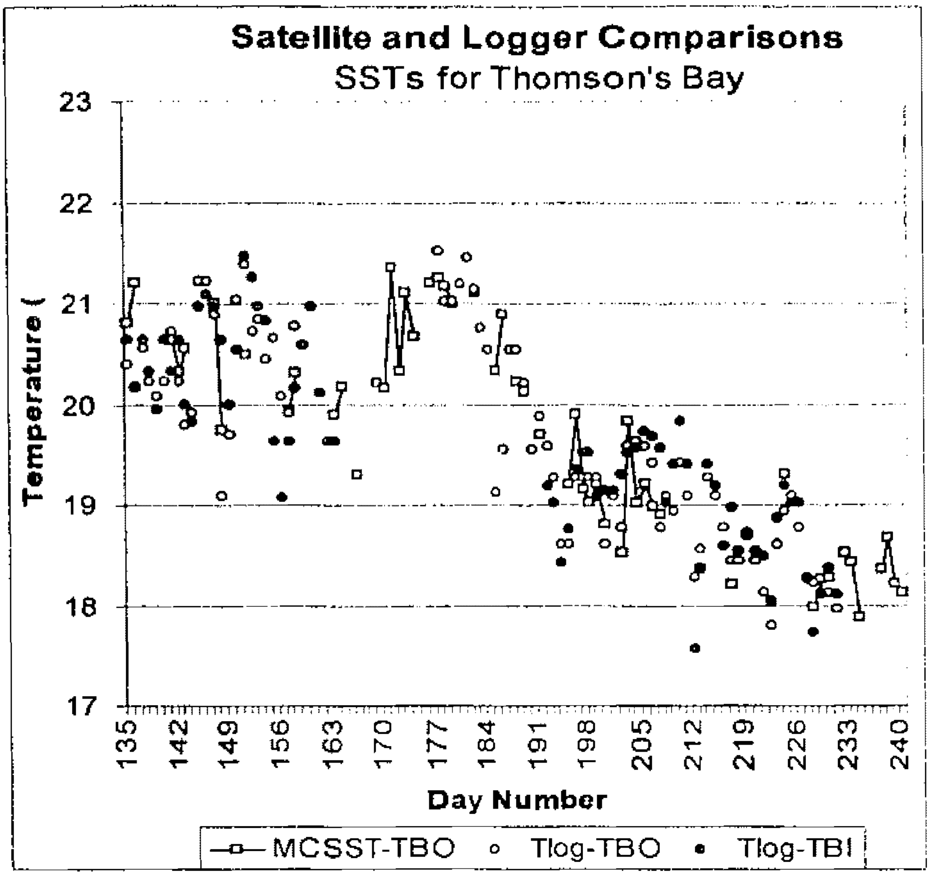

Figure 7.3 (b) – Satellite derived data, utilising MCSST, and logger derived data for the period May-September 2001, at Thomson's Bay.

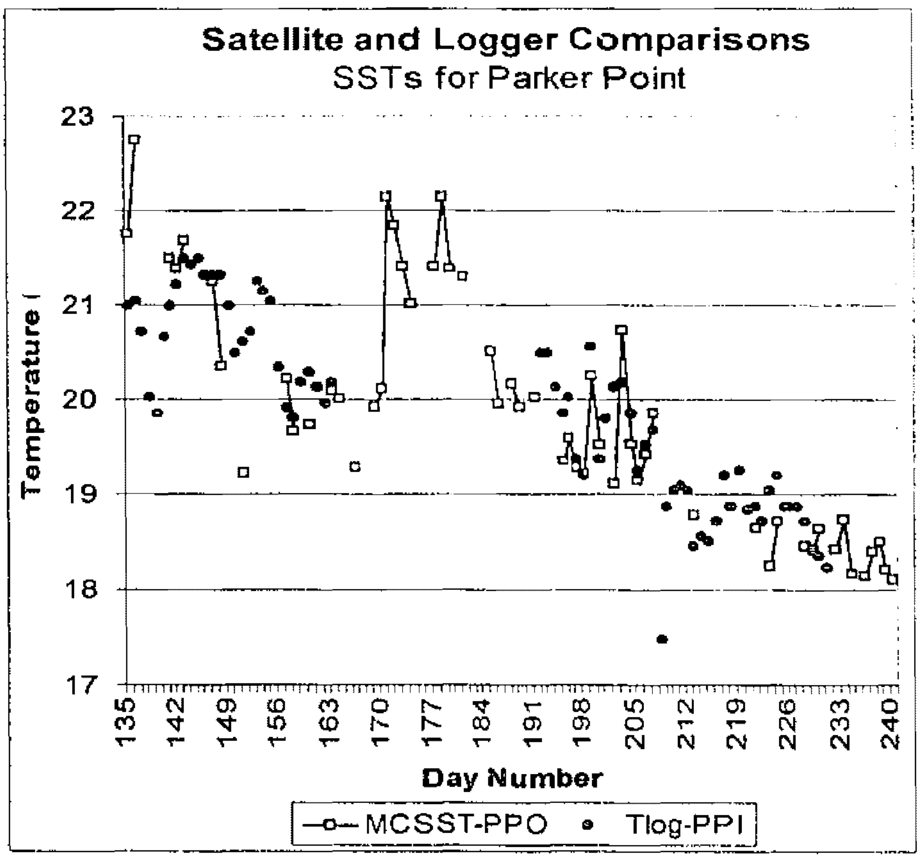

Figure 7.3 (c) – Satellite derived data, utilising MCSST, and logger-derived data for the period May-September 2001, at Parker Point.

Table 7.3 - Mean satellite-derived data, utilising MCSSST, for nearshore sites at Geordie Bay, Thomson's Bay and Parker Point, Rottnest Island, for the period Jan 1995 - August 2001

Month	Year	GBI	TBI	PPI	Month	Year	GBI	TBI	PPI	Month	Year	GBI	TBI	PPI	Month	Year	GBI	TBI	PPI
Jan.	1995	21.31	21.43	21.55	Jan.	1997	23.64	23.58	23.30	Jan.	1999	22.03	22.23	22.06	Jan.	2001	21.77	22.02	21.67
Feb.		21.64	21.63	21.85	Feb.		23.08	22.96	22.80	Feb.		22.98	23.17	22.89	Feb.		22.03	22.22	21.92
Mar.		21.49	21.60	21.82	Mar.		22.38	22.39	22.29	Mar.		22.89	22.69	23.10	Mar.		22.07	22.36	22.19
Apr.		22.51	22.32	22.35	Apr.		22.83	23.11	22.93	Apr.		24.43	24.20	24.46	Apr.		21.76	21.73	22.07
May.		21.15	21.07	21.37	May.		21.85	21.06	21.35	May.		23.04	22.60	22.20	May.		21.14	20.63	21.54
Jun.		20.10	19.38	20.22	Jun.		20.04	19.85	20.01	Jun.		21.09	20.67	20.97	Jun.		20.75	20.46	20.51
Jul.		19.57	19.30	19.92	Jul.		18.95	18.97	19.13	Jul.		19.60	19.54	19.68	Jul.		19.76	19.52	19.72
Aug.		18.86	18.22	18.85	Aug.		18.51	18.60	18.83	Aug.		19.41	19.13	18.88	Aug.		18.50	18.31	18.44
Sep.		19.27	19.20	19.24	Sep.		19.07	18.88	18.93	Sep.		18.71	18.71	19.06	Sep.				
Oct.		19.60	19.63	19.65	Oct.		19.63	19.68	19.29	Oct.		18.66	18.81	18.93	Oct.				
Nov.		20.16	20.53	20.29	Nov.		20.02	20.17	19.89	Nov.		19.63	19.60	19.48	Nov.				
Dec.		21.47	21.68	21.33	Dec.		21.54	21.59	21.44	Dec.		22.39	22.39	22.46	Dec.				
Jan.	1996	22.47	22.78	22.52	Jan.	1998	22.19	22.25	22.06	Jan.	2000	23.58	23.57	23.59					
Feb.		23.80	23.79	23.69	Feb.		21.72	21.75	21.50	Feb.		23.38	23.24	23.49					
Mar.		22.84	22.90	22.99	Mar.		22.60	22.35	22.30	Mar.		22.66	22.82	22.77					
Apr.		22.78	22.64	22.74	Apr.		22.26	22.09	22.26	Apr.		22.78	22.90	22.40					
May.		21.93	21.49	21.85	May.		21.86	21.82	21.91	May.		22.32	21.88	22.57					
Jun.		21.17	21.15	21.24	Jun.		20.68	20.24	20.60	Jun.		20.86	20.70	21.35					
Jul.		20.32	19.31	20.11	Jul.		19.61	19.31	20.02	Jul.		19.05	18.74	18.43					
Aug.		19.25	18.70	19.32	Aug.		19.18	18.88	19.03	Aug.		18.31	18.08	18.44					
Sep.		19.65	19.41	19.28	Sep.		19.00	18.95	18.81	Sep.		18.73	18.94	19.13					
Oct.		20.14	19.81	19.34	Oct.		18.96	18.76	18.85	Oct.		19.22	19.15	19.08					
Nov.		20.90	20.61	20.69	Nov.		20.24	20.33	20.11	Nov.		20.36	20.55	20.45					
Dec.		21.47	21.71	21.30	Dec.		21.75	21.69	21.45	Dec.		20.66	21.10	20.58					